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FINAL REPORT

SHUTTLE CRYOGENICS SUPPLY SYSTEM

OPTIMIZATION STUDY

VOLUME II

TECHNICAL REPORT

Sections 4 Through 9

CONTRACT NAS9-11330

Prepared for Manned Spacecraft Center
by
Manned Space Programs, Space Systems Division

LOCKHEED MISSILES & SPACE COMPANY, INC.
A SUBSIDIARY OF LOCKHEED AIRCRAFT CORPORATION

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FOREWORD

This Final Report provides the results obtained in the Shuttle Cryogenics Supply System Optimization Study, NAS9-11330, performed by Lockheed Missiles & Space Company (LMSC) under contract to the National Aeronautics and Space Administration, Manned Spacecraft Center, Houston, Texas. The study was under the technical direction of Mr. T. L. Davies, Cryogenics Section of the Power Generation Branch, Propulsion and Power Division. Technical effort producing these results was performed in the period from October 1970 to June 1973.

The Final Report is published in eleven volumes*:

Volume I	– Executive Summary
Volumes II, III, and IV	– Technical Report
Volume VA-1 and VA-2	– Math Model – Users Manual
Volume VB-1, VB-2, VB-3 and BV-4	– Math Model – Programmers Manual
Volume VI	– Appendixes

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*The Table of Contents for all volumes appears in Volume I only.
Section 12 in Volume III contains the List of References for Volumes I through IV.

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Section 4

SHUTTLE CONFIGURATIONS

Shuttle configurations were considered to be necessary in order to establish the range of goemetric factors required for the analysis. The configurations employed were selected from the concurrent Phase B shuttle studies. The configurations were selected from delta wing configurations in February, 1971.

The selected configurations were the North American-Rockwell and the McDonnell-Douglas high crossrange orbiter.

4.1 ORBIT MANEUVERING PROPELLANT SUPPLY (OMPS)

The Orbit Maneuver Propellant Supply configurations provide a range of feedline lengths and diameters. Since feedline designs were not available in sufficient detail to allow detailed evaluations, Lockheed prepared feedline designs to indicate the location of components.

<u>North American-Rockwell Orbiter - Orbit Maneuvering Propulsion</u>

The NAR orbiter is presented in Figures 4.1-1 and 4.1-3. The LO_2 feedline configuration has aft spherical tanks feeding three engines. This configuration provides the longest oxygen feedlines for aft located tanks. The LH_2 tanks are located in a relatively aft location providing the shortest feedlines.

The feedline configurations prepared for these designs are presented in Figures 4.1-2 and 4.1-4. The indicated feedline sizes were only the nominal selected sizes and not those resulting from optimization studies.

McDonnell-Douglas Orbiter - Orbit Maneuvering Propulsion

The MDC orbiter is presented in Figures 4.1-5 and 4.1-7. The LO_2 tanks are aft, providing propellants to two engines. The feedlines provide a short configuration. The LH_2 tank is located forward.

The feedline component layouts are presented in Figures 4.1-6 and 4.1-8.

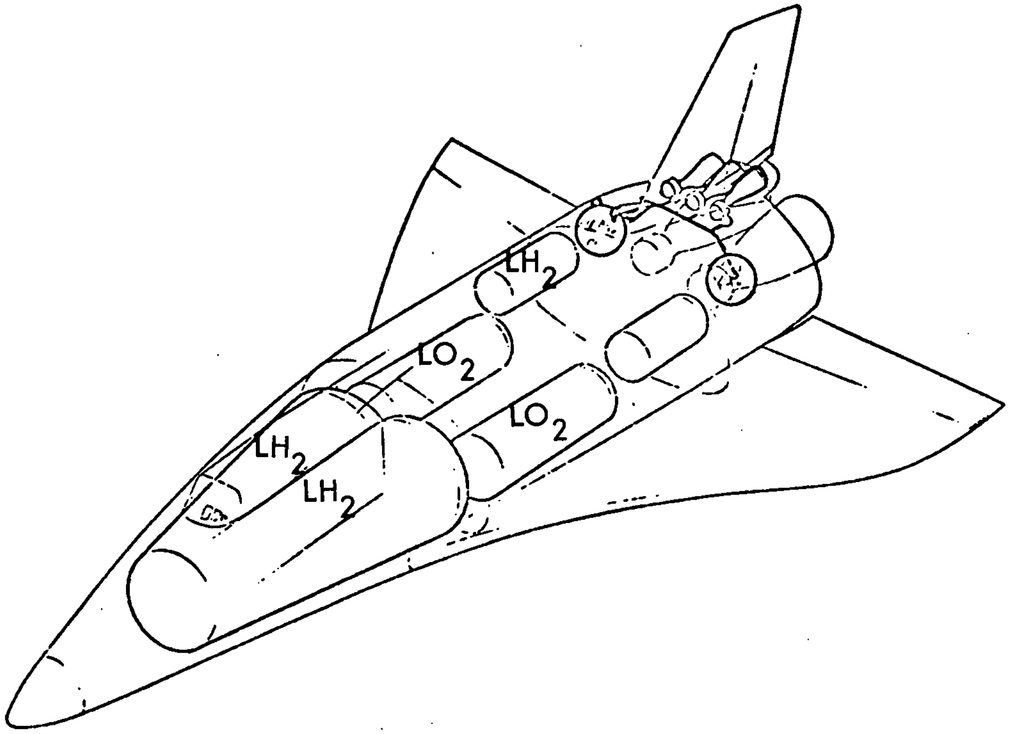
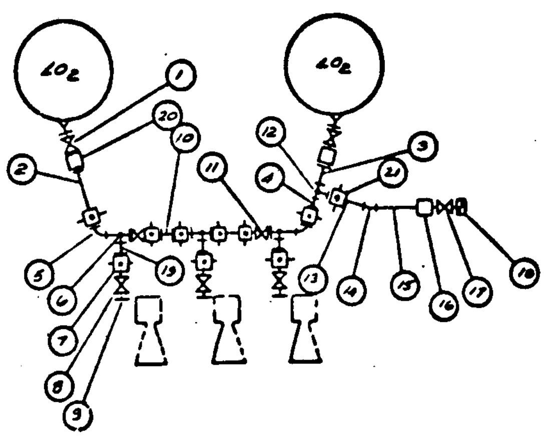


Fig. 4.1-1 NAR Orbiter LO_2, OMS Feed/Fill Configuration



KEY

1. TANK SHUTOFF VALVE
2. 4 IN. LINE - 100 IN. LONG
3. 4 IN. LINE - 50 IN. LONG
4. 4 IN. LINE - 40 IN. LONG
5. 60 DEG ELBOW - 2 PLACES
6. TEE - 4 IN. TO 3 IN. (3)
7. GIMBALLED BELLOWS (9)
8. ENGINE PREVALVE (3)
9. PUMP INTERFACE FLANGE (3)
10. 4 IN. LINE - 30 IN. LONG
11. ENGINE SELECTOR VALVE (2)
12. FILL TEE - 3 IN. TO 2 IN.
13. 2 IN. LINE - 80 IN. LONG
14. 45 DEG ELBOW
15. 2 IN. LINE - 110 IN. LONG
16. PRESSURE VOLUME COMPENSATOR
17. FILL SHUTOFF VALVE
18. FILL DISCONNECT
19. 3 IN. SHORT LINE (3)
20. PRESSURE VOLUME COMPENSATOR
21. GIMBALLED BELLOWS

Fig. 4.1-2 NAR Orbiter LO_2 OMS Feed/Fill Schematic

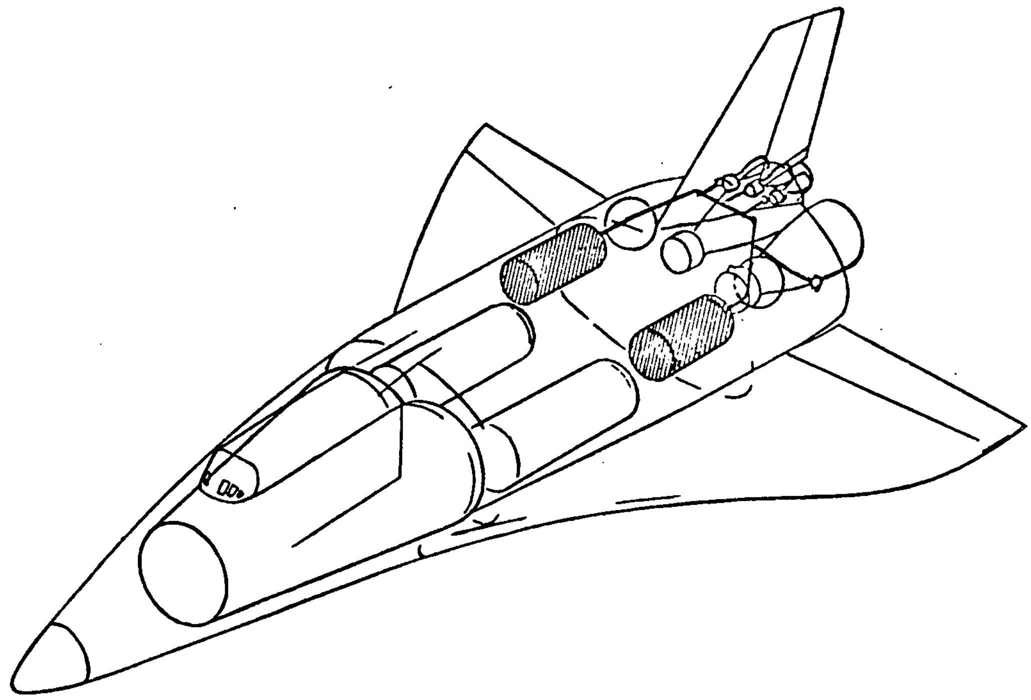
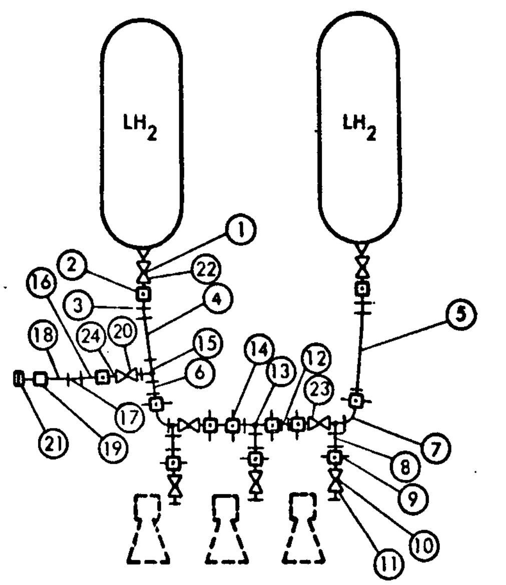


Fig. 4.1-3 NAR Orbiter LH_2 OMS Feed/Fill Configuration



KEY

1. TANK SHUTOFF VALVE (2)
2. 4 IN. LINE - 70 IN. LONG (EXP 0.28 IN.)(2)
3. 20 DEG ELBOW (2)
4. 4 IN. LINE - 90 IN. LONG (EXP 0.37 IN.)
5. 4 IN. LINE - 140 IN. LONG (EXP 0.57 IN.)
6. 4 IN. LINE - 40 IN. LONG (EXP 1.64 IN.)
7. 70 DEG ELBOW (2)
8. 3 IN. SHORT LINE (3)
9. RESTRAINED EXP BELLOWS (3)
10. ENGINE PREVALVE (3)
11. PUMP INTERFACE FLANGE (3)
12. 3 IN. LINE - 30 IN. LONG (EXP 0.12) (2)
13. TEE - 4 IN. TO 3 IN. (3)
14. GIMBALLED BELLOWS
15. FILL TEE - 4 IN. TO 2 IN.
16. 2 IN. LINE - 60 IN. LONG (EXP 0.25 IN.)
17. 45 DEG ELBOW
18. 2 IN. LINE - 50 IN. LONG (EXP 0.20 IN.)
19. PRESSURE VOLUME COMPENSATOR
20. FILL SHUTOFF VALVE
21. FILL DISCONNECT
22. PRESSURE VOLUME COMPENSATOR (2)
23. ENGINE SELECTOR SHUTOFF VALVE (2)
24. GIMBALLED BELLOWS

Fig. 4.1-4 NAR Orbiter LH_2 OMS Feed/Fill Schematic

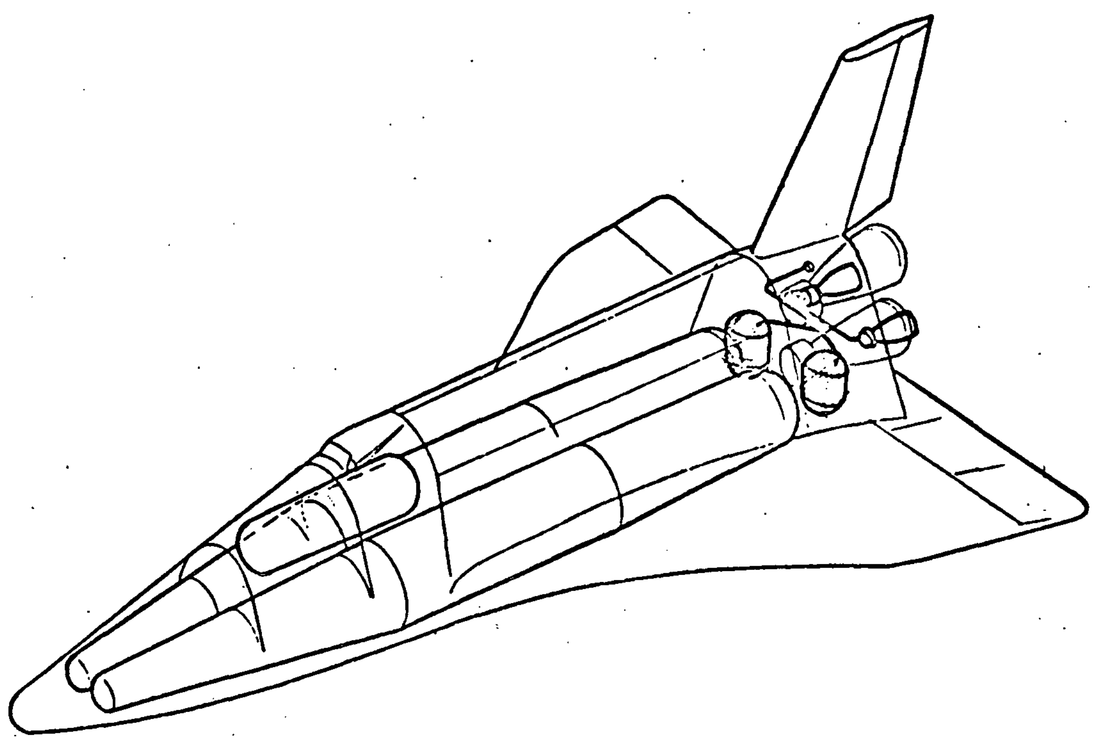
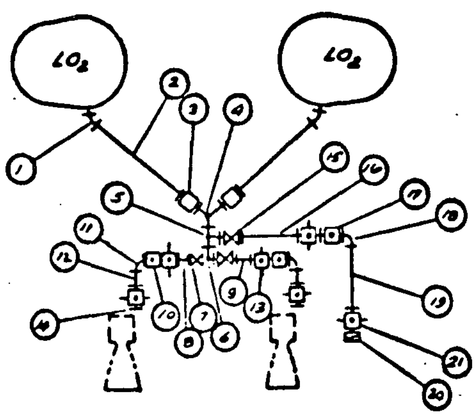


Fig. 4.1-5 MDC Orbiter LO_2 OMS Feed/Fill Configuration



KEY

1. 40 DEG ELBOW (2)
2. 3 IN. LINE - 70 IN. LONG (EXP 0.27 IN.) (2)
3. PRESSURE VOLUME COMPENSATOR (2)
4. Y-FITTING - 100 DEG THROAT ANGLE
5. FEED/FILL TEE - 3 IN. TO 2 IN.
6. ENGINE FEED TEE
7. ENGINE PREVALVE (2)
8. 3 IN. LINE - 75 IN. LONG (EXP 0.28 IN.)
9. 3 IN. LINE - 85 IN. LONG (EXP. 0.32 IN.)
10. PIVOTED BELLOWS (2)
11. 90 DEG ELBOW (2)
12. 3 IN. LINE - 25 IN. LONG (EXP 0.95 IN.) (2)
13. GIMBALLED BELLOWS (4)
14. PUMP INTERFACE FLANGE (2)
15. FILL SHUTOFF VALVE
16. 2 IN. LINE - 25 IN. LONG (EXP 0.95 IN.)
17. PIVOTED BELLOWS
18. 90 DEG ELBOW
19. 2 IN. LINE - 40 IN. LONG (EXP 0.15 IN.)
20. FILL DISCONNECT
21. GIMBALLED BELLOWS

Fig. 4.1-6 MDC Orbiter LO_2 OMS Feed/Fill Schematic

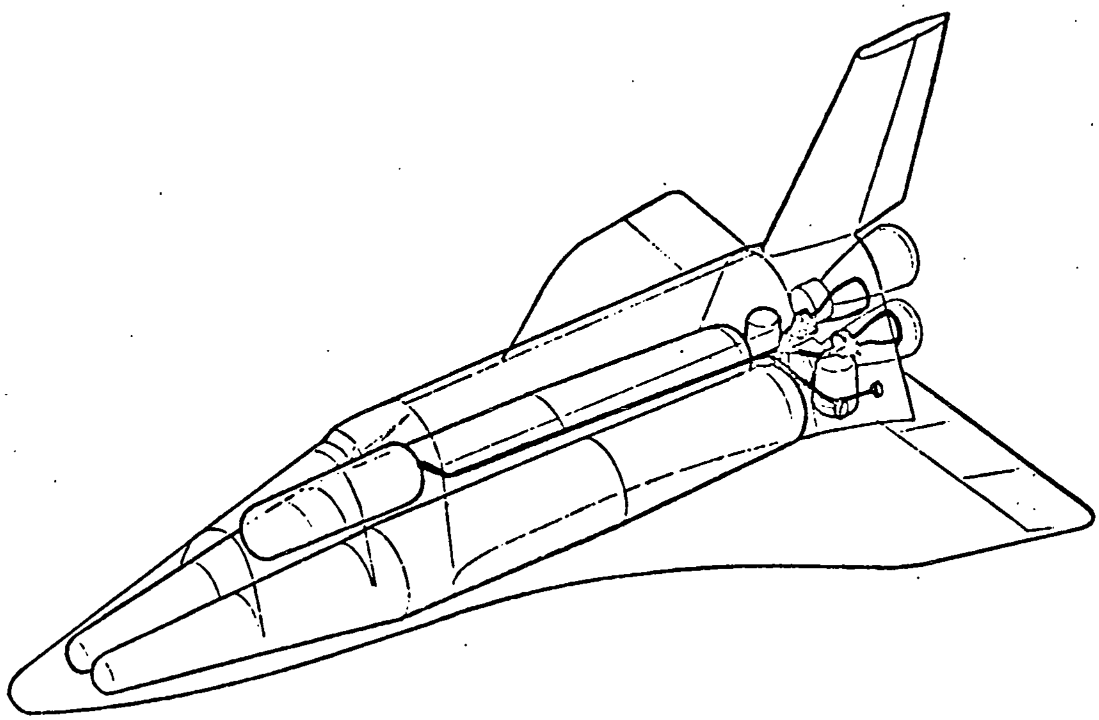
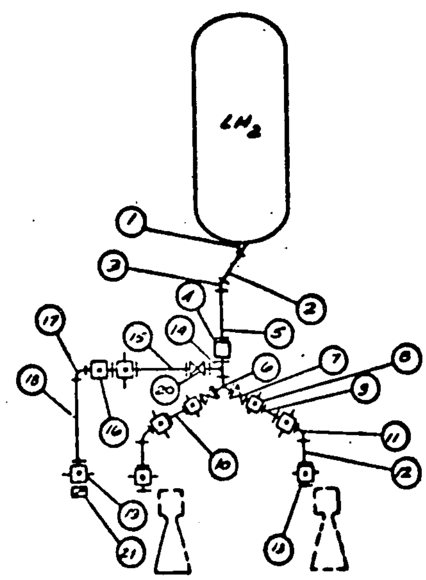


Fig. 4.1-7 MDC Orbiter LH_2 Feed/Fill Configuration



KEY

1. SUMP
2. 4 IN. LINE - 100 IN. LONG
3. 45 DEG ELBOW
4. PRESSURE VOLUME COMPENSATOR
5. 4 IN. LINE - 690 IN. LONG
6. Y-TRANSITION FITTING - 4 IN. TO 3 IN.
7. ENGINE PREVALVE (2)
8. GIMBALLED BELLOWS (6)
9. 3 IN. LINE - 100 IN. LONG
10. 3 IN. LINE - 150 IN. LONG
11. 45 DEG ELBOW (2)
12. 3 IN. SHORT LINE (2)
13. PUMP INTERFACE FLANGE (2)
14. FEED/FILL TEE
15. 2 IN. LINE - 200 IN. LONG
16. PIVOTED BELLOWS
17. 90 DEG BELLOWS
18. 2 IN. LINE - 200 IN. LONG
19. GIMBALLED BELLOWS
20. FILL SHUTOFF VALVE
21. FILL DISCONNECT

Fig. 4.1-8 MDC Orbiter LH_2 Feed/Fill Schematic

4.2 ORBIT INJECTION PROPELLANT SUPPLY (OIPS)

The Orbit Injection Propulsion supply concepts provide forward and aft locations for LH_2 and LO_2. Feedline configurations were prepared to provide a basis for the concept data.

North American-Rockwell Orbiter - Orbit Injection Propulsion

The NAR orbiter is presented in Figures 4.2-1 and 4.2-3. The LO_2 tanks are located in the midregion of the vehicle. The LH_2 tank is located forward. This configuration provides the shortest LO_2 lines and the longest LH_2 lines.

The feedline configurations prepared are presented in Figures 4.2-2 and 4.2-4. Only approximate feedline sizes are presented.

McDonnell-Douglas Orbiter - Orbit Injection Propulsion

The MDC orbiter employs common bulkhead tanks. The LO_2 tanks are forward, providing the maximum feedline lengths. The LH_2 tanks are aft. The configurations are presented in Figures 4.2-5 and 4.2-7.

The feedline configurations with approximate sizes are presented in Figures 4.2-6 and 4.2-8.

Propellant Transfer Systems

At the time these investigations were performed, consideration was being given to transfer of propellants from the orbit maneuvering propulsion supply to the orbit inspection supply for abort conditions. The configurations are presented in Figures 4.2-9 through 4.2-12.

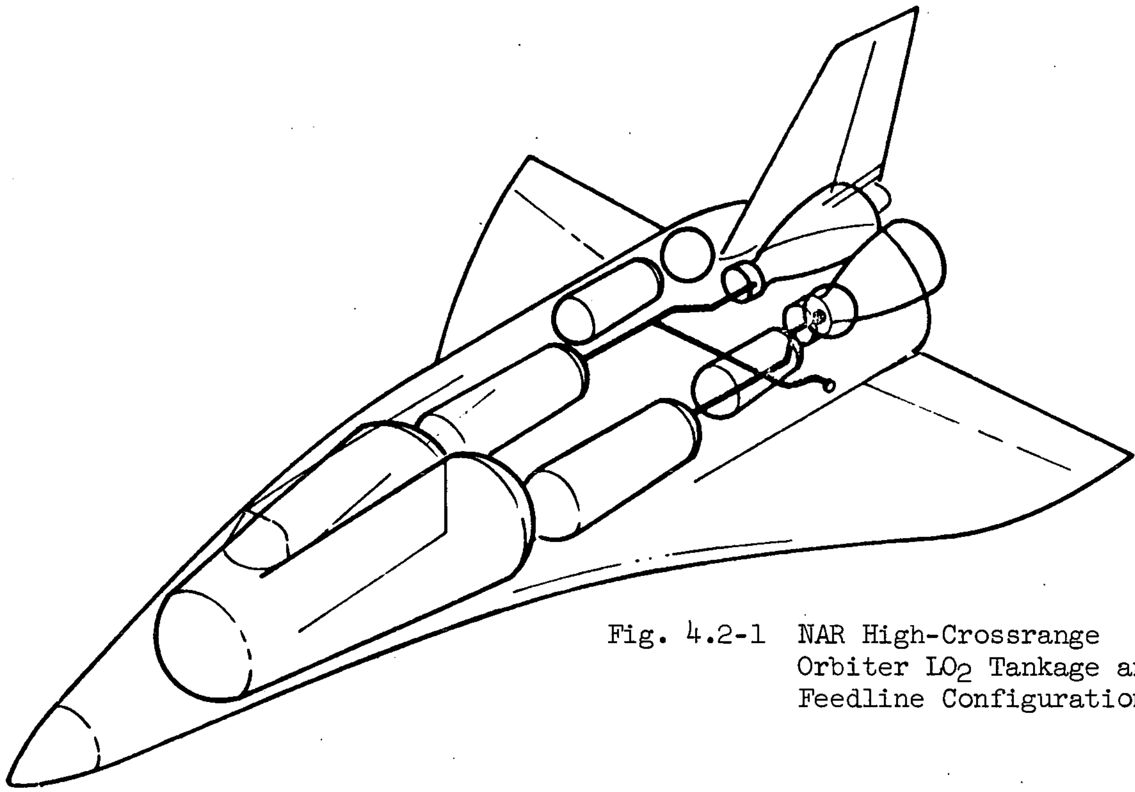
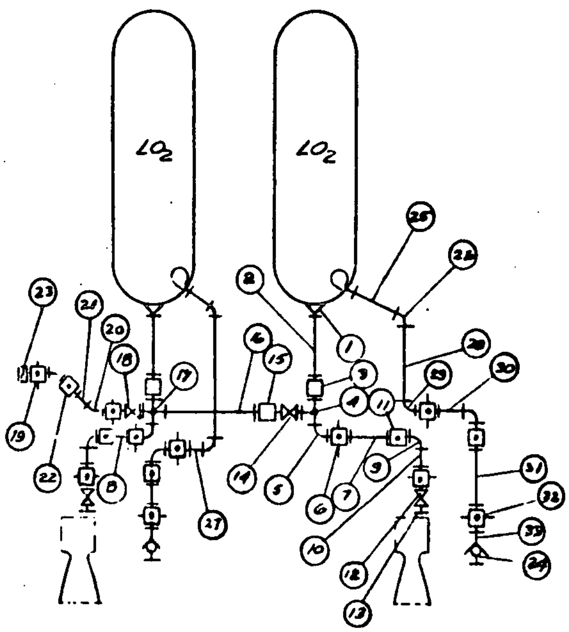


Fig. 4.2-1 NAR High-Crossrange Orbiter LO_2 Tankage and Feedline Configuration



KEY

1. SUMP (2)
2. 14 IN. LINE - 300 IN. LONG (2)
3. PRESSURE VOLUME COMPENSATOR
4. FEED/FILL/INTERTANK TEE
5. 90 DEG ELBOW (2)
6. GIMBALLED BELLOWS (4)
7. 14 IN. LINE - 140 IN. LONG
8. 14 IN. LINE - 80 IN. LONG
9. 90 DEG ELBOW (2)
10. 14 IN. SHORT LINE (2)
11. PIVOTED BELLOWS (2)
12. ENGINE PREVALVE (2)
13. PUMP INTERFACE FLANGE (2)
14. INTERTANK VALVE
15. PRESSURE VOLUME COMPENSATOR
16. 14 IN. LINE - 200 IN. LONG
17. FEED/FILL/INTERTANK JUNCTION
18. FILL SHUTOFF VALVE
19. GIMBALLED BELLOWS
20. 45 DEG ELBOW (2)
21. 8 IN. LINE - 170 IN. LONG
22. PIVOTED BELLOWS
23. FILL DISCONNECT
24. CHECK VALVE (2)
25. 1 IN. SHORT LINE (2)
26. 45 DEG ELBOW (2)
27. 1 IN. LINE - 80 IN. LONG
28. 1 IN. LINE - 300 IN. LONG (2)
29. 90 DEG ELBOW (4)
30. 1 IN. LINE - 140 IN. LONG
31. 1 IN. SHORT LINE (2)
32. GIMBALLED BELLOWS (2)
33. 1 IN. SHORT LINE

Fig. 4.2-2 NAR High-Crossrange Orbiter LO_2 Tankage and Feedline Schematic

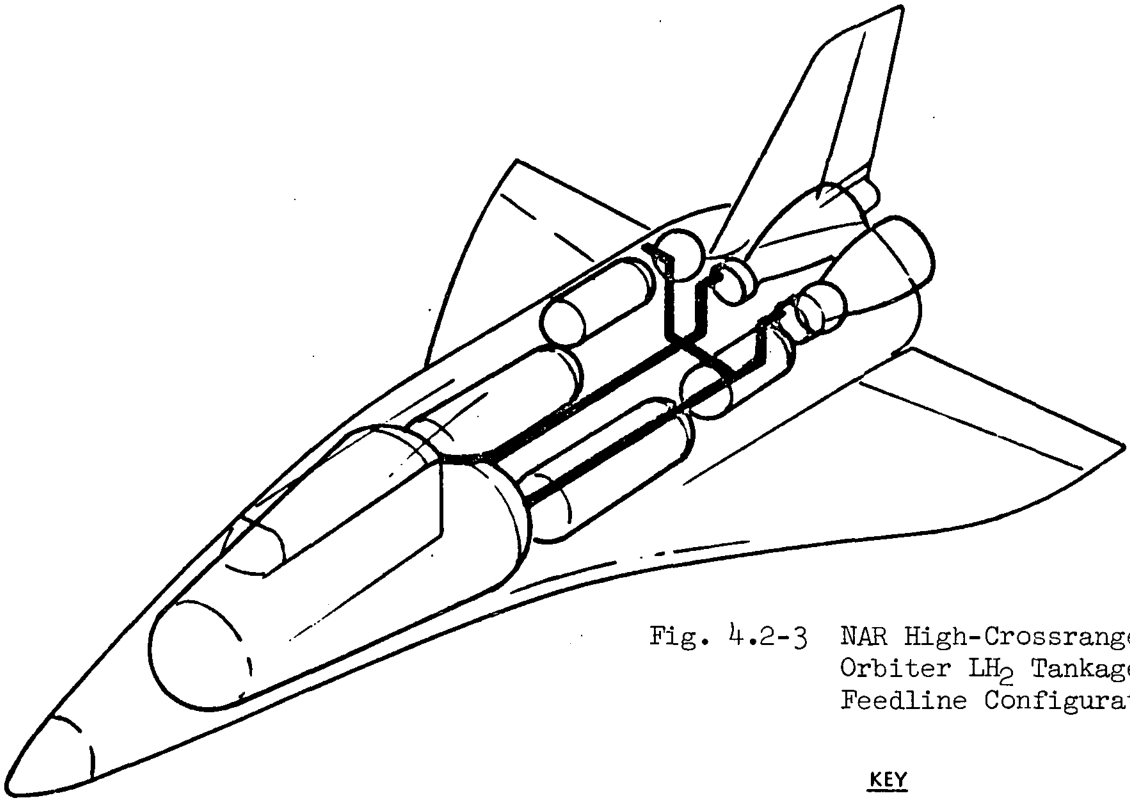
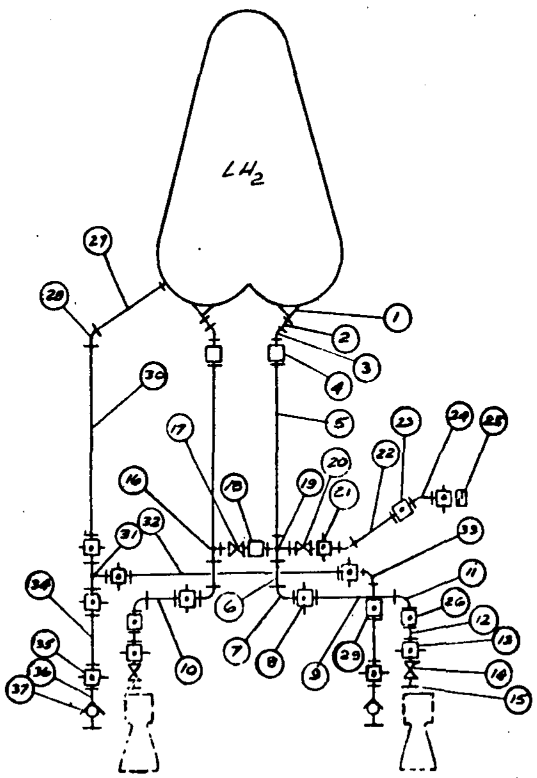


Fig. 4.2-3 NAR High-Crossrange Orbiter LH_2 Tankage and Feedline Configuration



KEY

1. SUMP (2)
2. 14 IN. LINE - 70 IN. LONG (EXP 0.29 IN.) (2)
3. 45 DEG ELBOW (2)
4. PRESSURE VOLUME COMPENSATOR (2)
5. 14 IN. LINE - 680 IN. LONG (EXP 2.90 IN.) (2)
6. 14 IN. LINE - 80 IN. LONG (EXP 0.33 IN.) (2)
7. 90 DEG ELBOW (2)
8. GIMBALLED BELLOWS (2)
9. 14 IN. LINE - 80 IN. LONG (EXP 0.33 IN.)
10. 14 IN. LINE - SAME AS 9
11. 90 DEG ELBOW (2)
12. 14 IN. SHORT LINE (2)
13. GIMBALLED BELLOWS (4)
14. ENGINE PREVALVE (2)
15. PUMP INTERFACE FLANGE
16. FEED/FILL/INTERTANK TEE
17. INTERTANK VALVE
18. PRESSURE VOLUME COMPENSATOR
19. FEED/FILL/INTERTANK JUNCTION
20. FILL SHUTOFF VALVE
21. GIMBALLED BELLOWS (2)
22. 8 IN. LINE - 170 IN. LONG (EXP 0.70 IN.)
23. PIVOTED BELLOWS
24. 30 DEG ELBOW (2)
25. FILL DISCONNECT
26. PIVOTED BELLOWS (2)
27. 1 IN. LINE - 60 IN. LONG (EXP 0.25 IN.)
28. 45 DEG ELBOW
29. PIVOTED BELLOWS
30. 1 IN. LINE - 680 IN. LONG (EXP 2.80 IN.) (2)
31. FEED/FILL TEE
32. 1 IN. SHORT LINE
33. ELBOW
34. 1 IN. SHORT LINE
35. GIMBALLED BELLOWS (6)
36. 1 IN. SHORT LINE
37. CHECK VALVE

Fig. 4.2-4 NAR High-Crossrange Orbiter LH_2 Tankage and Feedline Schematic

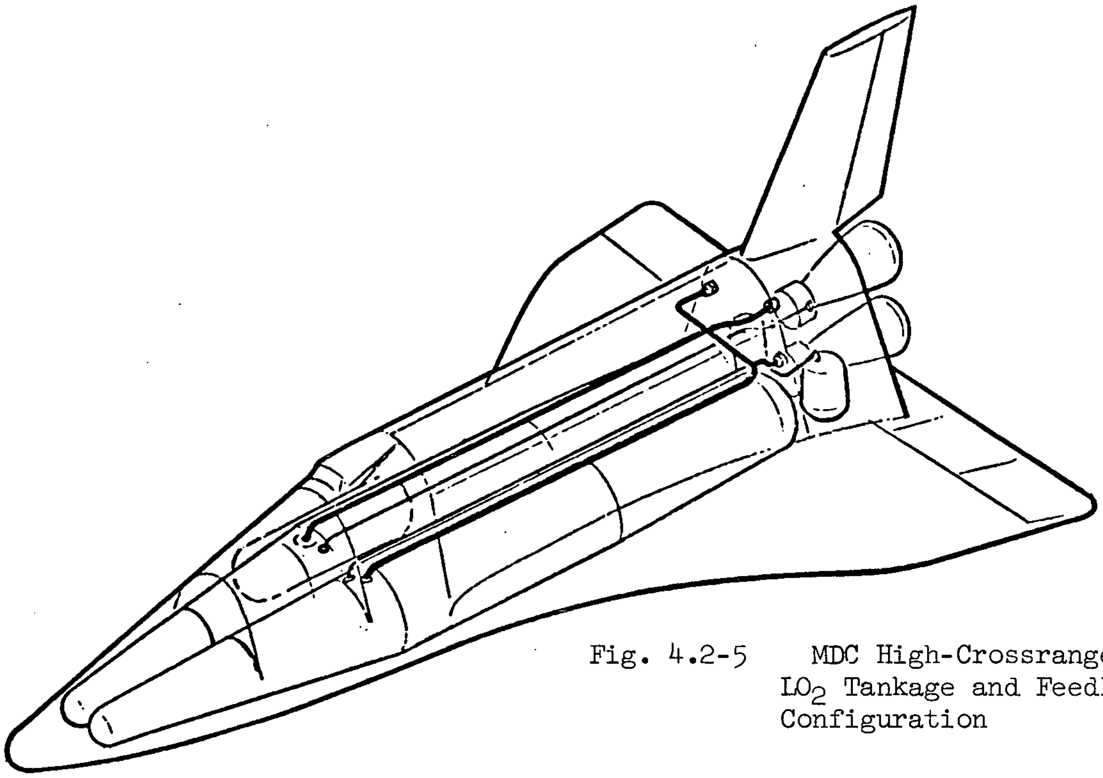
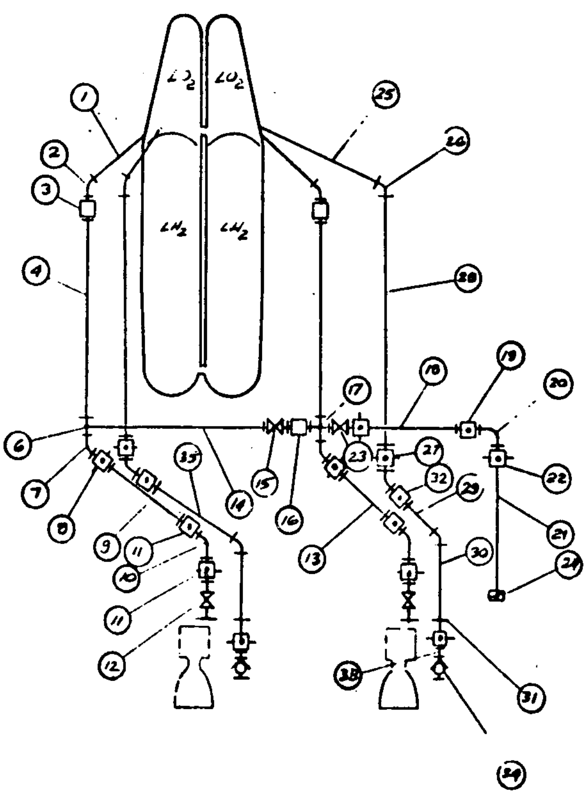


Fig. 4.2-5 MDC High-Crossrange LO_2 Tankage and Feedline Configuration



KEY

1. 14 IN. SHORT LINE (2)
2. 45 DEG ELBOW (2)
3. PRESSURE VOLUME COMPENSATOR (2)
4. 14 IN. LINE - 700 IN. LONG (EXP 2.65 IN.) (2)
5. PRESSURE VOLUME COMPENSATOR
6. FEED/FILL/INTERTANK TEE
7. 45 DEG ELBOW
8. GIMBALLED BELLOWS (4)
9. 14 IN. LINE - 120 IN. LONG (EXP 0.46 IN.)
10. 45 DEG ELBOW
11. PIVOTED BELLOWS (2)
12. ENGINE PREVALVE
13. 14 IN. LINE - 90 IN. LONG (EXP 0.34 IN.)
14. 14 IN. LINE - 160 IN. LONG (EXP 0.61 IN.)
15. INTERTANK VALVE
16. PRESSURE VOLUME COMPENSATOR
17. FILL/FEED/INTERTANK JUNCTION
18. 8 IN. LINE - 120 IN. LONG (EXP 0.46 IN.)
19. PIVOTED BELLOWS
20. 90 DEG ELBOW
21. 8 IN. LINE - 180 IN. LONG (EXP 0.69 IN.)
22. GIMBALLED BELLOWS
23. FILL SHUTOFF VALVE
24. FILL DISCONNECT
25. 1 IN. SHORT LINE
26. 45 DEG ELBOW (6)
27. GIMBALLED BELLOWS (2)
28. 1 IN. LINE - 700 IN. LONG (EXP 2.65 IN.) (2)
29. 1 IN. LINE - 90 IN. LONG (EXP 0.34 IN.)
30. 1 IN. LINE - 70 IN. LONG (EXP 0.29 IN.) (2)
31. INTERFACE FLANGED FEEDTHRU (2)
32. PIVOTED BELLOWS (2)
33. 1 IN. SHORT LINE (2)
34. CHECK VALVE (2)
35. 1 IN. LINE - 120 IN. LONG (EXP 0.46 IN.)

Fig. 4.2-6 MDC High-Crossrange LO_2 Tankage and Feedline Schematic

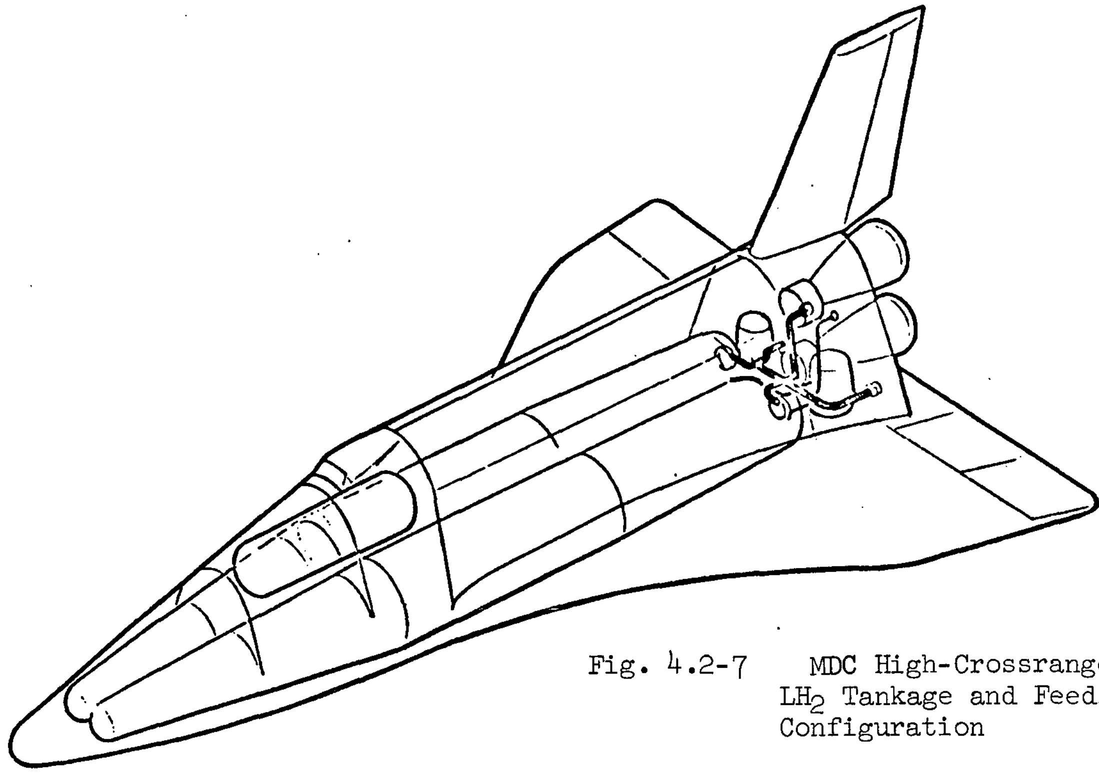
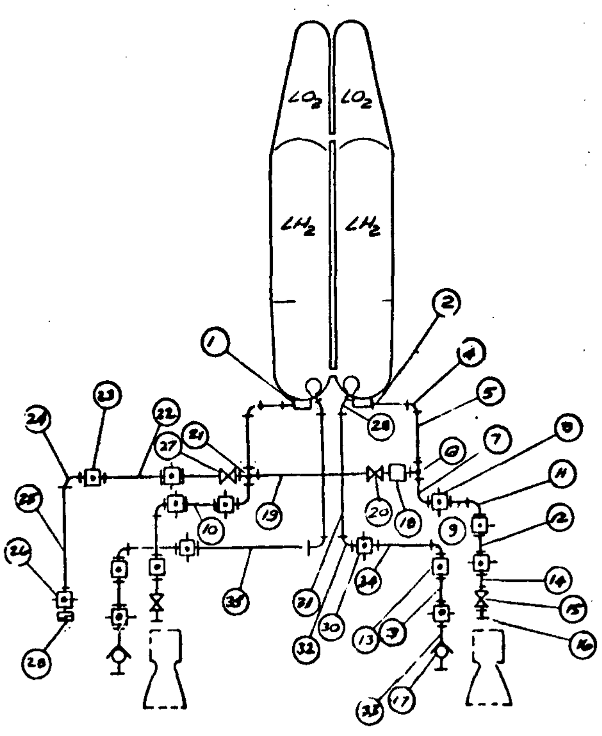


Fig. 4.2-7 MDC High-Crossrange LH_2 Tankage and Feedline Configuration



KEY

1. SUMP - FUEL (2)
2. 14 IN. LINE - 72 IN. LONG (2)
3. 1 IN. LINE - 72 IN. LONG (2)
4. 90 DEG ELBOW (2)
5. 14 IN. LINE - 96 IN. LONG (2)
6. FEED/FILL/INTERTANK TEE
7. 90 DEG ELBOW (2)
8. GIMBALLED BELLOWS (6)
9. 14 IN. SHORT LINE
10. 14 IN. LINE - 100 IN. LONG
11. 90 DEG ELBOW (2)
12. 14 IN. LINE - 72 IN. LONG (2)
13. PIVOTED BELLOWS (2)
14. 14 IN. SHORT LINE (2)
15. ENGINE PREVALVE (2)
16. PUMP INTERFACE FLANGE (2)
17. CHECK VALVE (2)
18. PRESSURE VOLUME COMPENSATOR
19. 14 IN. LINE - 60 IN. LONG (2)
20. INTERTANK VALVE
21. INTERTANK JUNCTION
22. 8 IN. LINE - 90 IN. LONG (2)
23. PIVOTED BELLOWS
24. 90 DEG ELBOW
25. 3 IN. LINE - 220 IN. LONG
26. GIMBALLED BELLOWS (2)
27. FILL SHUTOFF VALVE
28. FILL DISCONNECT
29. 45 DEG ELBOW (2)
30. GIMBALLED BELLOWS (4)
31. 1 IN. LINE - 96 IN. LONG (2)
32. 90 DEG ELBOW (4)
33. 1 IN. SHORT LINE (2)
34. 1 IN. SHORT LINE
35. 1 IN. LINE - 50 IN. LONG

Fig. 4.2-8 MDC High-Crossrange LH_2 Tankage and Feedline Schematic

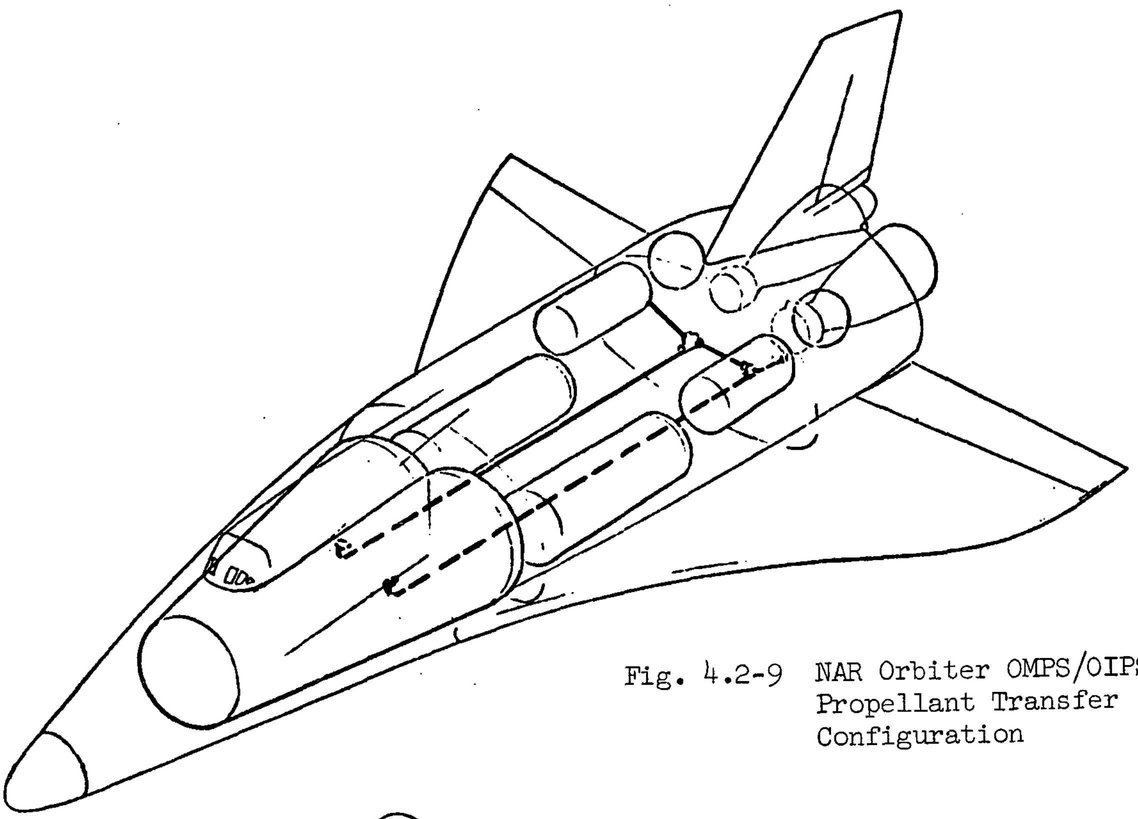
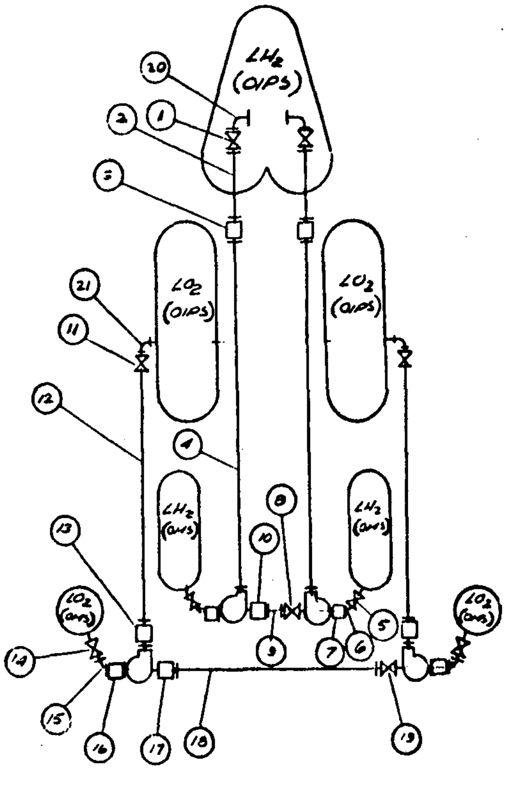


Fig. 4.2-9 NAR Orbiter OMPS/OIPS Propellant Transfer Configuration



KEY

1. TANK SHUTOFF VALVE (2)
2. 4 IN. LINE - 420 IN. LONG (EXP 1.72 IN.)(2)
3. PRESSURE VOLUME COMPENSATOR (2)
4. 4 IN. LINE - 750 IN. LONG (EXP 3.07 IN.)(2)
5. TRANSFER SYSTEM SHUTOFF VALVE (NC) (2)
6. 45 DEG ELBOW (2)
7. WIRE-BRAID SLEEVED BELLOWS (2)
8. TRANSFER VALVE (NC)
9. 4 IN. LINE - 180 IN. LONG (EXP 0.74 IN.)
10. RESTRAINED EXP BELLOWS
11. TANK SHUTOFF VALVE (2)
12. 4 IN. LINE - 600 IN. LONG (EXP 2.27 IN.)(2)
13. PRESSURE VOLUME COMPENSATOR (2)
14. TRANSFER SYSTEM SHUTOFF VALVE (NC) (2)
15. 45 DEG ELBOW (2)
16. WIRE-BRAID COVERED BELLOWS
17. PRESSURE VOLUME COMPENSATOR (2)
18. 4 IN. LINE - 100 IN. LONG (EXP 0.38 IN.)
19. TRANSFER VALVE (NC)
20. 90 DEG ELBOW (2)
21. 90 DEG ELBOW (2)

Fig. 4.2-10 NAR Orbiter OMPS/OIPS Propellant Transfer Schematic

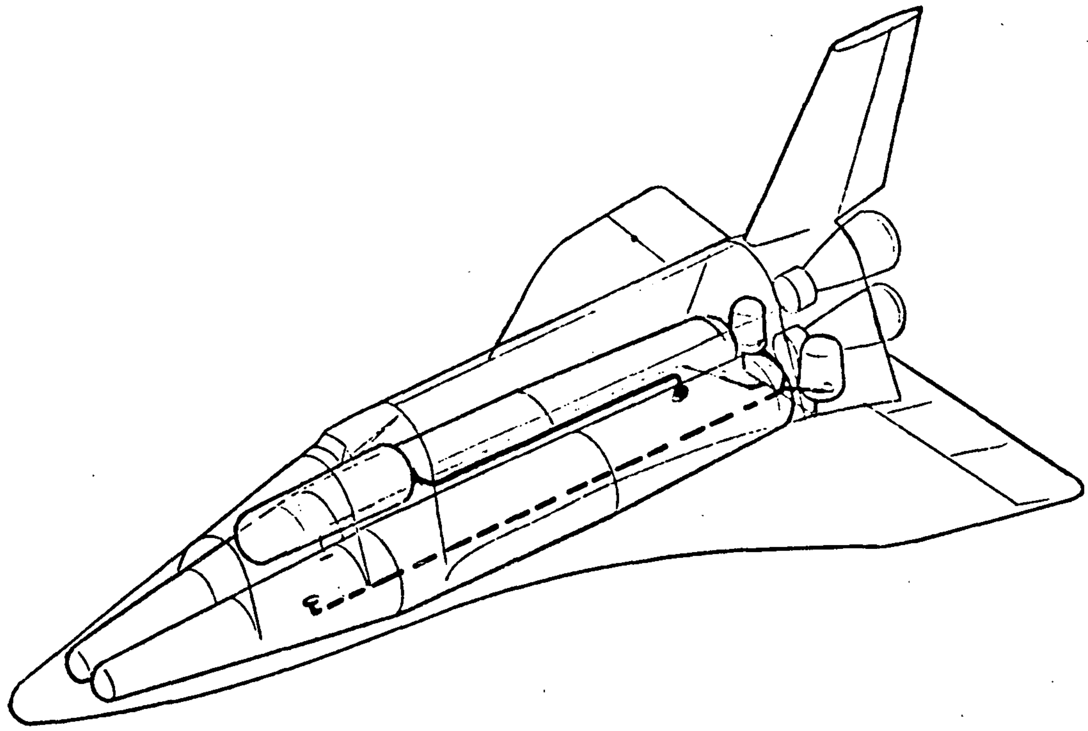
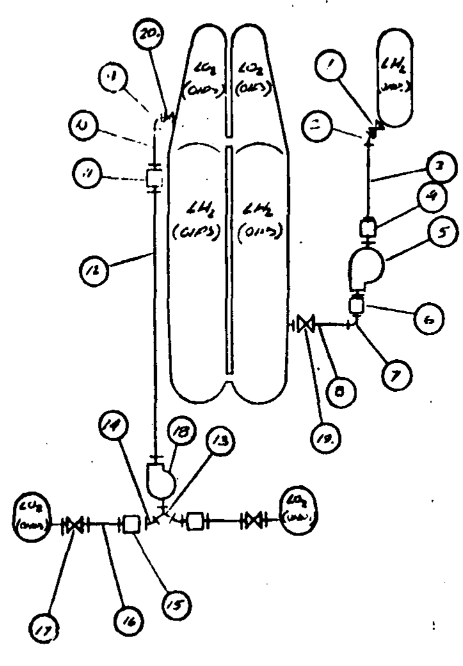


Fig. 4.2-11 MDC Orbiter OMPS/OIPS Propellant Transfer Configuration



KEY

1. TRANSFER SYSTEM SHUTOFF VALVE (NC)
2. 45 DEG ELBOW
3. 4 IN. LINE - 450 IN. LONG (EXP 1.84 IN.)
4. PRESSURE VOLUME COMPENSATOR
5. PROPELLANT TRANSFER PUMP
6. WIRE-BRAID COVERED BELLOWS
7. 90 DEG ELBOW
8. 4 IN. SHORT LINE
9. 90 DEG ELBOW
10. 4 IN. LINE - 140 IN. LONG (EXP 0.53 IN.)
11. PRESSURE VOLUME COMPENSATOR
12. 4 IN. LINE - 1050 IN. LONG (EXP 4.00 IN.)
13. Y-FITTING
14. 45 DEG ELBOW (2)
15. PRESSURE VOLUME COMPENSATOR (2)
16. 4 IN. LINE - 80 IN. LONG (EXP 0.29 IN.)(2)
17. TRANSFER SYSTEM SHUTOFF VALVE (NC)(2)
18. PROPELLANT TRANSFER PUMP
19. TRANSFER SYSTEM SHUTOFF VALVE (NC)
20. TRANSFER SYSTEM SHUTOFF VALVE (NC)

Fig. 4.2-12 MDC Orbiter OMPS/OIPS Propellant Transfer Schematic

Section 5

CRITERIA AND REQUIREMENTS

In the study, an effort was made to separate criteria and requirements and to consider these from completely different standpoints.

Criteria were considered to be factors that were imposed by ground rules or which were relatively independent of changes in the vehicle designs or operation.

Requirements were defined as mission and vehicle imposed factors which constitute performance goals for the systems, or which must be accomplished in order for the system to achieve the required operating conditions.

The Space Shuttle is planned as a multipurpose vehicle capable of performing several basic missions. The missions identified by NASA as being of major interest in future space activities are:

- Space station/base logistics supply
- Satellite placement and retrieval
- Delivery of propulsive stages and payloads
- Delivery of propellants
- Satellite service and maintenance

These missions all involve the delivery of payloads to and from earth orbit. The first mission, space station/base logistics supply, has been selected as the design reference mission. The primary activity involved in the delivery of cargo and/or passengers to and from the space station, which is located in a 55 deg inclined orbit at an altitude of 270 nm. The reference mission is considered to be of 7 days duration from liftoff of the space shuttle until landing of the orbiter.

5.1 CRITERIA

The criteria established for the study were derived from NASA documents, Phase B shuttle contracts, and consideration derived in this contract.

5.1.1 Mission Criteria

The design reference selected is logistics supply of the space station. The station is presumed to be in a circular orbit at an altitude of 270 nautical miles and with an inclination of 55 degrees. The shuttle will be used to transfer equipment and personnel to and from the station. Total mission duration is 7 days and it is anticipated that the orbiter will be docked to the station for the majority of this time. In addition to its 25,000 lb capacity, the vehicle will be able to carry two crew members and two cargo handlers. The orbiter will be designed so that its crew compartment environment (pressure and composition) is compatible with the space station. EVA activities will not be required during the transfer of personnel or payload to or from the space station.

For study purposes, the nominal mission is divided into the following phases:

Phase	Duration
Prelaunch	From the beginning of cryogenic loading until liftoff.
Ascent	From launch until orbit is achieved.
Orbit Maneuvers	From insertion to orbit transfer and docking.
Orbit Operations	Activities while orbiter is docked.
Deorbit Maneuvers	From undocking until entry begins at 400,000 ft altitude.
Entry	From 400,000 ft altitude until landing.
Post-flight	From landing until postflight ground operations are completed.

Two abbreviated mission time-lines have been defined in this study to evaluate the cryogenic system operations. The first assumes that rendezvous with the space station is accomplished during the third orbital revolution after liftoff. It is representative of the shortest time from liftoff until docking. The second case assumes that rendezvous will not be accomplished until the seventeenth revolution, and represents the longest expected time from liftoff until docking. Both cases assume that the orbiter makes a direct entry from the space station altitude. Selected key events for each of these missions are presented in Tables 5.1-1 and 5.1-2. These time-lines are used to define individual system duty cycles, the relationship between operations of the various systems, etc.

Representative ascent and entry trajectories for the high crossrange vehicle, taken from NAR Phase B activity are shown in Figure 5.1-1 and 5.2-2, respectively. The reference orbit parameters are shown in Figure 5.1-3. Note that for the time-lines presented previously, the deorbit time would differ somewhat depending on whether a high-crossrange or low-crossrange maneuver is to be performed, since the time from 400,000 feet to landing differs for these vehicles. Typical entry acceleration profiles were desired for subsystem studies. A typical profile is presented in Figure 5.1-4.

Table 5.1-1

ABBREVIATED MISSION TIME LINE FOR ORBITER

THIRD REV. RENDEZVOUS DIRECT REENTRY	
MISSION ELAPSED TIME (hr:min:sec)	MISSION EVENT
-02:00:00	Begin childown for cryogenic loading
-00:02:00	Disconnect all line
00:00:00	Vehicle Lift-off
00:03:16	Staging
00:03:26	Main engines ignition
00:07:22	Main engines shutdown
00:49:15	Phasing - 1st OMPS engine burn
01:34:47	Transfer to 270 nm altitude
02:21:45	Circularize orbit at 270 nm
05:06:06	Dock to station
163:34:00	Separate from station
166:34:00	Begin deorbit retroburn OMPS engine ignition
168:00:00	Land
168:10:00	Complete rollout
: :	Complete vehicle inerting

Table 5.1-2

ABBREVIATED MISSION TIME LINE FOR ORBITER

17TH REV. RENDEZVOUS DIRECT REENTRY	
MISSION ELAPSED TIME (hr:min:sec)	MISSION EVENT
-02:00:00	Begin childown for cryogenic loading
-00:02:00	Disconnect all lines
00:00:00	Vehicle lift-off
00:03:16	Staging
00:03:26	Main engines ignition
00:07:22	Main engines shutdown
00:49:14	Phasing - 1st OMPS engine burn
22:14:20	Transfer to 270 nm altitude
23:00:08	Circularize orbit
25:44:30	Dock to station
163:34:00	Separate from station
166:34:00	Begin deorbit retroburn - OMPS engine
168:00:00	Land
168:10:00	Complete rollout
	Complete vehicle inerting

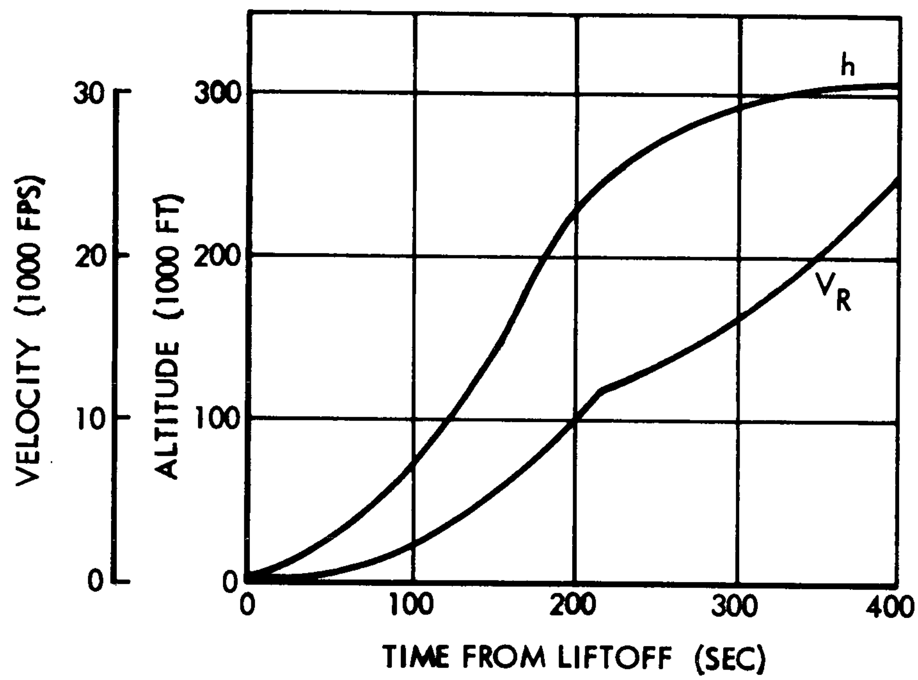


Fig. 5.1-1 High-Crossrange Orbiter Ascent Trajectory

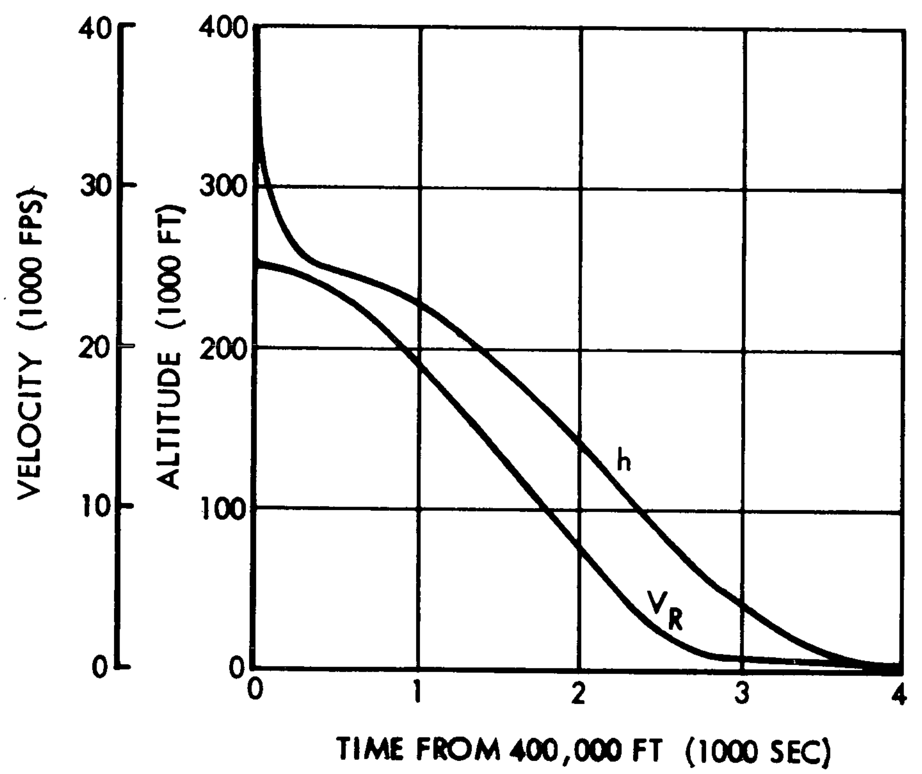


Fig. 5.1-2 High-Crossrange Orbiter Entry Trajectory

REFERENCE ORBIT PARAMETERS

ALTITUDE	=	270 x 270 NM
INCLINATION	=	55 DEG
β	=	0
VEHICLE ORIENTATION	=	BOTTOM OF EARTH

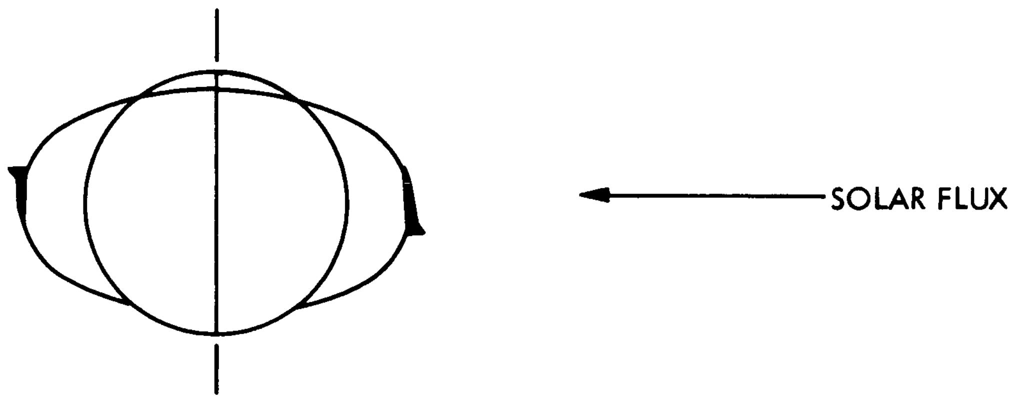


Fig. 5.1-3 Reference Orbit Parameters

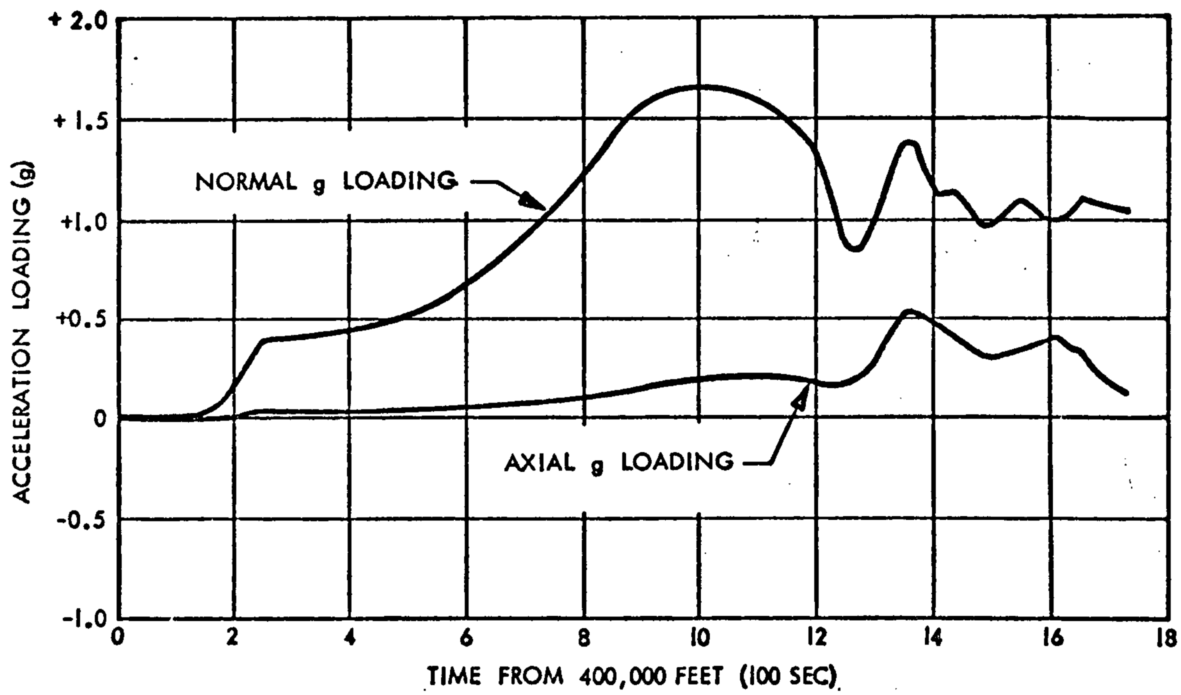


Fig. 5.1-4 Typical Entry Acceleration (g) – High Crossrange

5.1.2 Lifetime and Reuse Criteria

The criteria for the Space Shuttle have been established as a lifetime of 10 years of 100 flights, whichever is first. These criteria were applied to those items that are not normally replaced, such as tankage structural attachments and plumbing.

It was recognized that components subject to wearout (such as valving) and materials which degrade from environmental effects (such as insulators) will be replaced before the failure rate of these is increased as a result of use.

5.1.3 Structural Criteria

Material properties were established as the "A" allowable values of MIL-HDBK-5A or equivalent values based on probability and confidence. Property values at operating temperature were used. Structural factors are shown in Table 5.1-3.

Table 5.1-3

STRUCTURAL FACTORS

Part	Yield Factor	Proof Factor	Ultimate Factor
Orbit Injection Tanks	**1.1**	**1.05**	**1.4**
Other Cryogenic Tankage	**–**	**1.5**	**2.0**
Lines and Fittings	**–**	**1.5**	**2.5**
High Pressure Vessels, Pneumatic and Hydraulic Tanks	**–**	**1.5**	**2.0**

For structural attachments, safety factors of 1.4 during ascent and 1.5 during reentry will apply. For loads which are applied rapidly, a dynamic load factor of 1.5 will be used to determine limit loads.

Because the shuttle vehicle is intended to have a long life with many reuses, the effects of cyclic loading on flow propagation are significant. Fracture mechanics techniques provide suitable mechanisms for evaluating these effects. For materials where sufficient data on fracture toughness and sufficient knowledge of operating conditions can be defined, proof pressure and ultimate factors of safety will be determined from these data.

5.1.4 Structural Temperatures

Structure temperature criteria were established for the High Crossrange Orbiter. The data are presented in Figure 5.1-5 (Reference 5-1).

5.1.5 Propellant and Reactant Tank Sizing Criteria

All tank volumes included a 3-percent ullage factor, over and above the maximum propellant or reactant loading.

The propellant and reactant densities employed for sizing were the boiling densities. The boiling densities are for the conditions that the propellant or reactant are boiling from heat input when loaded prior to launch. Gas bubbles are present in the propellant or reactant. The resulting densities are:

Liquid Hydrogen - 4.28 $16/ft^3$
Liquid Oxygen - 70.2 $16/ft^3$

5.1.6 Safety Criteria

The following criteria will be supplied to the individual systems. For integrated systems, the more stringent criteria will be applied to those components which are common to the several subsystems.

Fail-operational means that the system will be capable of successfully completing the mission. Fail-safe means that the vehicle and crew can return safely to earth after a failure. The life support and fuel cell systems shall have a 24-hour return capability remaining after reaching the fail-safe condition. See Table 5.1-4.

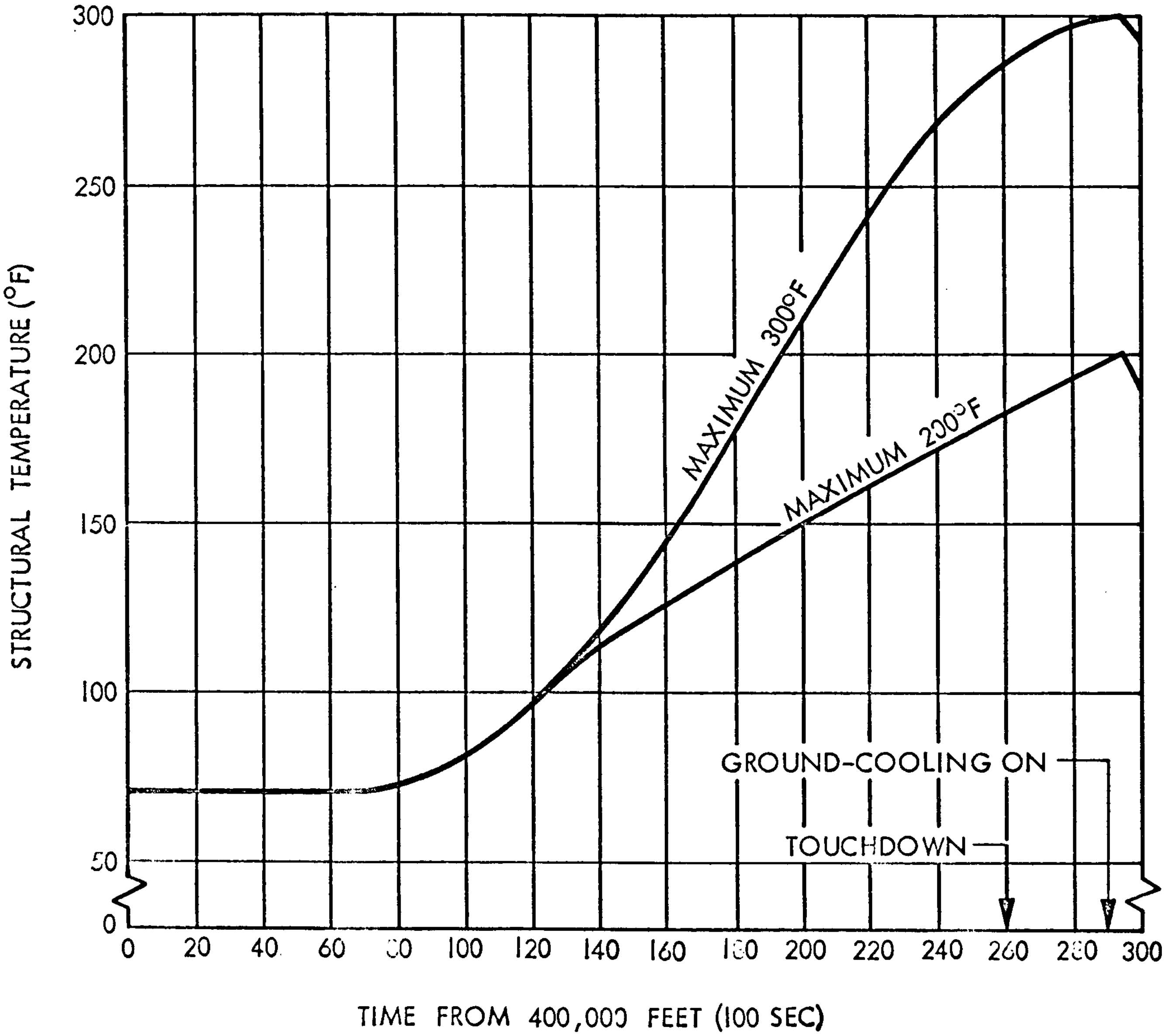


Fig. 5.1-5 Typical High-Crossrange Orbiter Reentry Structural Temperatures

Table 5.1-4

FAILURE CRITERIA

Subsystem	First Failure	Second Failure	Third Failure
Life Support Supply	Operational	Safe	–
Power Generation Supply			
Fuel Cell	Operational	Operational	Safe
Auxiliary Power	Operational	Operational	Safe
Propellant Supply			
Orbit Injection	Operational	Safe	–
Orbit Maneuver	Operational	Safe	–
Attitude Control	Operational	Safe	–
Airbreathing Engine	Operational	Safe	–
Purge, Inert, and Pneumatic	Operational	Safe	–

Failure criteria, such as fail-operational, fail-safe; or fail-operational, fail-operational, fail-safe will not apply to tankage and lines in the supply systems.

The criteria for design of the cryogenic systems for safety include:

- Pressure relief should be provided throughout the system, including plumbing.
- Air liquefaction must be prevented.
- Venting must be controlled in the atmosphere.
- All vents must be located to preclude vapor concentrations within the vehicle.
- Vents for O_2 and H_2 must be prevented from freezing shut.
- Tankage implosion must be prevented during loading and entry.

5.1.7 Abort Criteria

NASA has established a requirement for an intact abort capability for the space shuttle. This poses a particular requirement on the main propellant supply system during the ascent phase of the mission.

It is necessary to consider under what conditions the cryogenic supply system could require that a mission be aborted. In general, a mission abort is indicated whenever a system is in a fail-safe condition. This criterion will be applied to the cryogenic supply systems.

5.1.8 Technology Status

Tentatively, the status of component development will be established to be consistent with original Phase B study Space Shuttle Program schedules. To meet this goal, selected components should be equivalent to 1972 state-of-the-art. Further, any selected components must be capable of being suitably developed for 1976 Shuttle flights.

5.1.9 Ground Operations

Cryogenic loading operations will be accomplished within two hours, beginning with the vehicle in a standby condition. This is taken to mean that all necessary lines are connected and the systems are purged and ready for loading operations to begin. Simultaneous loading of the booster and orbiter will be permitted during this period.

5.1.10 Maintainability

The shuttle is to be designed for a two-week turnaround capability. As discussed earlier, life criteria for components provides for the possibility of replacement prior to the 100-mission life between major maintenance and overhaul. Any components for which part replacement is required should be installed so minimum replacement time is required. Replacement of the component or module, rather than replacement of the specific part, is considered acceptable to ease installation problems.

5.2 REQUIREMENTS

The requirements for the various subsystems were established from:

(1) requirements of the cryogenic consuming subsystem or unit (engine, fuel cell, auxiliary power unit, etc.)

(2) duty cycles

(3) interface requirements between subsystems.

References are provided regarding the sources of the requirements.

5.2.1 Orbit Maneuvering Propellant Supply

The Orbit Maneuvering Propellant Supply requirements were established from examination of data from a number of sources.

5.2.1.1 Orbit Maneuvering Propulsion Engine Requirements.

5.2.1.1.1 RL-10 Engines. The Pratt and Whitney Co. has a family of RL-10A-3 engines which are likely candidates for application to the OMS system. The pertinent data for this family is summarized in Table 5.2-1. Data presented were taken from Ref. 5-2. The RL-10A-3-3 is the only operational engine and currently is being employed on Centaur. Rated thrust of 15,000 lbf is achieved at a nominal chamber pressure of 400 psia at altitudes of 200,000 with the nozzle expansion ratio listed (57 to 1). Gasious helium is used to actuate valves for starting and stopping the engine. A prestart or childown period is required to cool the hydrogen and oxygen pumps to the desired temperature. This period is initiated by actuating the prestart solenoid valves to permit helium flow to the fuel and oxidizer inlet shut-off valves

Table 5.2-1

SUMMARY OF RL-10A-3 ENGINE CHARACTERISTICS

Model Number	Thrust 1000 lb	Throttle Range	Nom I_{sp} (sec)	Nozzle Expansion Ratio	NPSP (psi) Fuel	NPSP (psi) Ox	Propellant Bleed	Tank Head Idle	Dry Weight (lb)	Gimbal Angle (deg)	Run Time (sec)	Service Life (sec)	Number of Starts (spec min)
RL-10A-3-3	15	None	444	57	4	8	No	No	290	± 4.0	450	4000	20
-3-3A	15	None	444	57	2	4	H_2	No	297	± 4.0	450	4500	20
-3-4	17	None	444	56.7	-	-	-	-	300	± 4.0	470	2820	20
-3-5	20	?	437	40	-	-	?	-	300	± 4.0	470	2820	20
-3-6	10	None	450	84	4	8	No	No	275	-	470	4000	20
-3-7	15	10:1	444	57	2	4	H_2 & O_2	Yes	330	± 6.0	900	4000	50
-3-8	22.5	15:1	444	57	2	4	H_2 & O_2	Yes	350	± 6.0	900	4000	50

NOTES: 1. All engines have nominal mixture ratio of 5.0.

2. Minimum I_{sp} is 5 sec lower than nominal.

3. RL-10A-3-3 only operational engine.

to open them. Both fuel and oxidizer flow through the pumps and the thrust chamber and are vented overboard until chilling is completed. Starting is initiated by a signal to the start solenoid allowing helium to flow to open the main fuel shutoff valve. Ignition is achieved electrically when a combustible mixture is available. Shutdown is achieved by simultaneous removal of the signals to the start and prestart solenoid valves. This allows the helium actuation gas to be vented overboard, closing the fluid flow valves. All valves are automatically returned to the prestart position. The other engines listed in the table are variations in this basic engine that are or can be made available for OMS use. According to Ref. 5-2 the modifications required to provide other models have been generally demonstrated in ground tests by P&W or NASA.

The main limitation of the RL-10-3 families that affect their application to OMS is the present specified service life and number of starts. Mission models for the space station logistics supply mission indicate total operating times of between 755 sec and 815 sec are required (depending on the rendezvous orbit and whether the shuttle remains docked or separates and redocks). The number of starts range from 8 to 11 per mission. Reference 5-2 indicates the specified values that can be expected to increase with operational experience. Based on present data, it is estimated that at least 2 hours and 300 firings can be obtained without damage or performance degradation, with an eventual capability to reach 10 hours or more of service life. Thus, in initial service, the RL-10-3-3 or -3A would need checking of the start capability after two missions and complete engine inspection after four or five missions. This would require engine removal and activities equivalent to an engine overhaul. This approach is expected to increase service life to 2 to 3 hours between overhauls. The main areas of concern are the turbopump gears, bearings, and shaft seals, the bellows in both the thrust control and the main fuel shutoff valve, and the thermal cycle limitation on the present thrust chamber design.

P&W foresees no problem with run times longer than 450 sec. Efficient performance of high-orbit altitude missions will require an extension in run times. Assuming a vehicle weight of 300,000 lb., a maximum ΔV of about 700 ft/sec is all that can be obtained in a 450 sec burn. Orbit transfer ΔV of 100 to 1200 ft/sec (at both apogee and perigee) are required to transfer from 100 nm to 800 nm. Similarly, deorbit velocities of 1200 to 1300 ft/sec are needed for reentry from 800 nm. Run times up to 850 sec are required, if these velocities are to be achieved in a single burn.

Another operational requirement associated with the present engine design may be the use of helium pressure to provide sealing around the gearbox shaft in the turbopump. The present design apparently does not provide for a shutoff for the helium and it is continuously vented overboard at a small rate. However, excessive amounts of helium could be vented during a seven-day mission and means of eliminating this loss would have to be provided. Elimination of helium as an activating gas is also desirable.

5.2.1.1.2 Advanced OMPS engines. In addition to the RL-10 engines, advanced OMPS engines were examined in the studies. The assumed engine characteristics were:

Thrust	–	10,000 lb
Specific Impulse	–	444 and 456 sec

The assumed start transient for this engine is presented in Figure 5.2-1.

5.2.1.2 Orbit Maneuvering Propellant Supply System Requirements. The range of Orbit Maneuvering Propulsion System requirements are presented in Table 5.2-2. The ranges of data presented are representative of the RL-10 engine and the operation of two advanced engines at 20,000 lb thrust.

The duty cycles of use of the RL-10 engine at 15,000 lb thrust in the OMPS for two mission profiles are presented in Table 5.2-3.

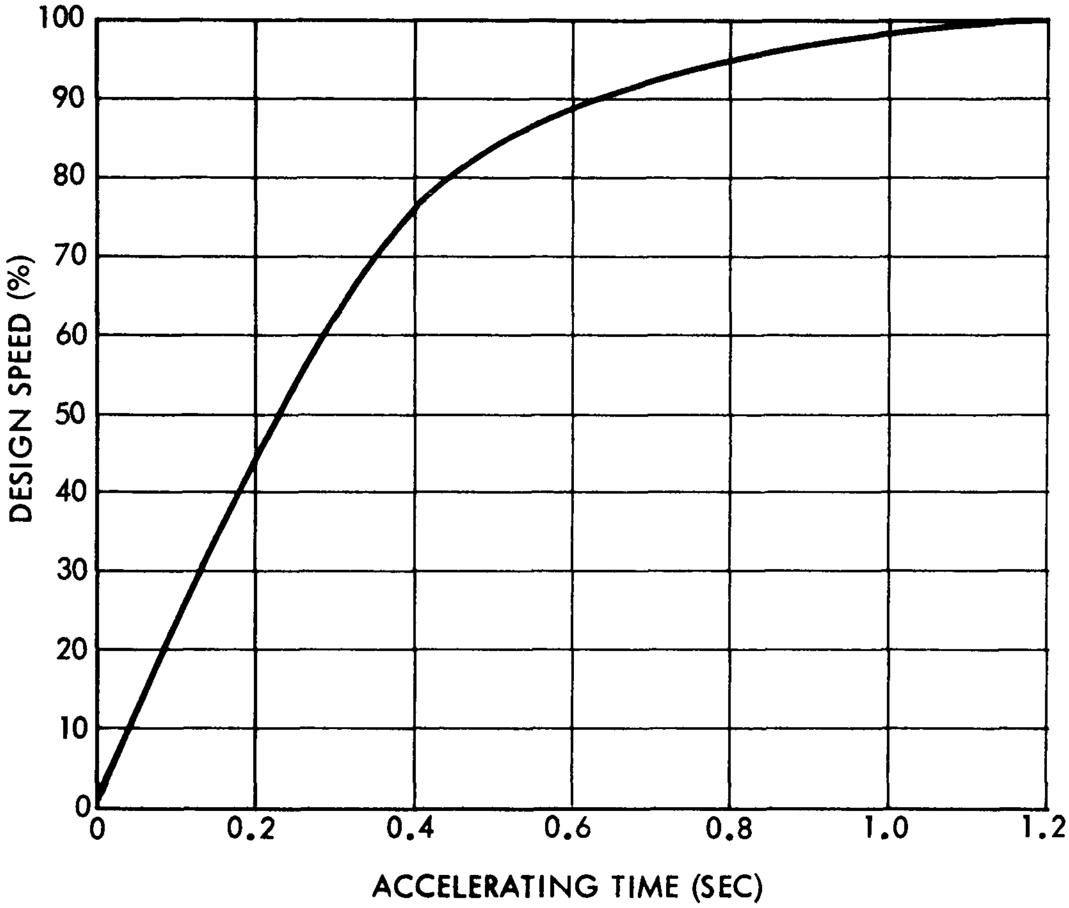


Fig. 5.2-1 Orbit Maneuvering Propulsion Advanced Engine Typical Start Transient

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Table 5.2-2

ORBIT MANEUVERING PROPELLANT SUPPLY SYSTEM

		O_2	H_2	Source Reference
Propellant Quantity*	Min Max	18,300 lb 27,000 lb	3700 lb 5400 lb	5-1, 5-3, 5-4, 5-5, 5-6
Propellant Flow Rate	Min Max	12.5 lb/sec 38.1 lb/sec	3.5 lb/sec 8.0 lb/sec	5-4, 5-5, 5-6, 5-7
Supply System Outlet Pressure (ΔP Above Vapor Pressure)	Nom	4 psi	2 psi	5-4, 5-7
Supply System Outlet Temperature		Subcooled liquid		5-8
Mixture Ratio (O/F)	Nom	5:1 ± 3%		5-8
Life: Operating	Total	Min – 14 hr Max – 22 hr		5-1, 5-6 5-7, 5-9 5-10
	Per Flight	Min – 500 sec** Max – 800 sec		5-1, 5-6 5-7, 5-9 5-10
	Flights	100		5-11
Nonoperating	Total	10 yr		5-11
	Orbital/ Flight	7 dy		5-11

Note:

* Quantity based on nominal delta-V of 1400 ft/sec. Tankage shall be sized for delta-V = 1900 ft/sec. A delta-V of 100 ft/sec out of the required on-orbit delta-V of 1500 ft/sec has been alloted to the ACPS.

** Total operating time based on operation at 20,000-lb thrust level.

Table 5.2-3

ORBIT MANEUVERING PROPULSION SYSTEM DUTY CYCLE – RL-10 ENGINE

	3rd Rev Rendezvous				17th Rev Rendezvous			
Event	Mission Ellapsed Time hr:min:sec	Time From Last Burn (hr)	[1] Burn Time Max/Min (sec)	[2] Propellant Used Max/Min (lb)	Mission Ellapsed Time	Time From Last Burn (hr)	[1] Burn Time Max/Min (sec)	[2] Propellant Used Max/Min (lb)
Phasing	00:49:15	–	206/173	7100/5920	00:49:14	–	77/64	2620/2200
Height	01:34:47	0.75	160/135	5500/4600	22:14:20	21.40	165/138	5640/4720
Coelliptic	02:21:45	0.79	15/12	685/420	23:00:08	0.77	137/115	4690/3930
TPI	03:50:56	1.48	12/10	422/355	24:34:23	1.58	12/10	424/355
Deorbit	166:34:00	162.72	280/234	9550/8000	166:34:00	141.99	279/234	9540/7980
Contingency	–	–	123/108	4350/3680	–	–	125/105	4280/3590
Total	–	–	796/672	27,607/ 22,975	–	–	795/666	27,194/ 22,775

1 Based on a thrust level of 15,000 lb.

2 Based on a specific impulse of 439 sec.

5.2.2 Orbit Injection Propellant Supply

The Orbit Injection Propellant Supply subsystem requirements have relatively wide variations as a result of the Phase B results. All of the requirements stated are for the two-stage fully reusable vehicle.

5.2.2.1 Orbit Injection Propulsion Engine Requirement. The engine requirements used in the study were principally based upon the Shuttle Engine Interface Control Document 13M15000 B, dated 1 March 1971. Engine Contractor data were employed in specific evaluation. The overall engine characteristics are presented in Table 5.2.-4.

Table 5.2-4

ORBIT INJECTION PROPULSION ENGINE CHARACTERISTICS

Parameter	Value
Thrust	632 ± 10K lb
Isp (vacuum)	459 ± 3 sec
Expansion Ratio	150:1
Flow Rate	1385 lb/sec
Oxidizer/Fuel Ratio	6
NPSH	See additional data

In the near future, the referenced Interface Control Document may not be available so selected data of particular interest to the propellant supply are presented.

In Figure 5.2-2, the prestart propellant conditions are presented. It should be noted that the propellant temperature must be kept within a narrow range when starting at lower pressures. If the orbiter is started under zero gravity conditions, then the tank pressure to temperature relationships are critical.

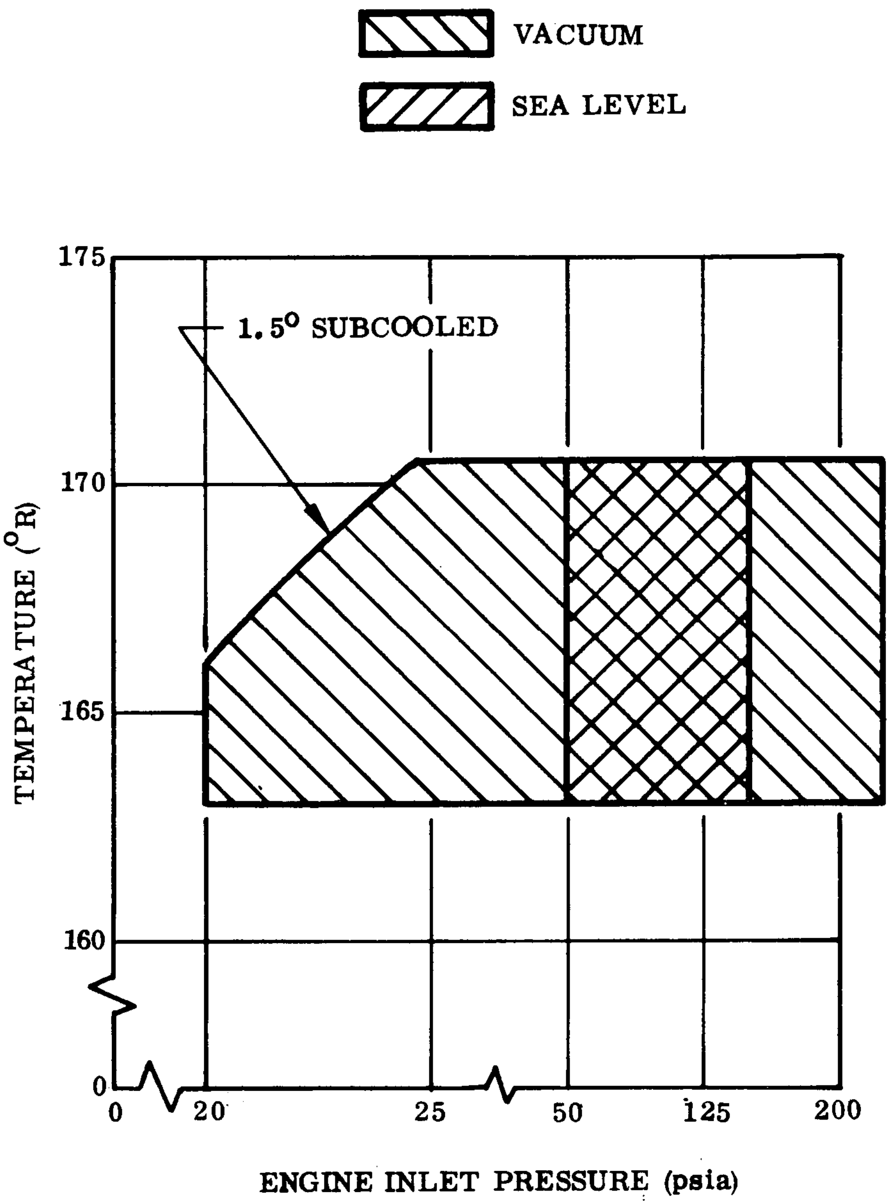


Fig. 5.2-2a Prestart Propellant Condition — Oxidizer

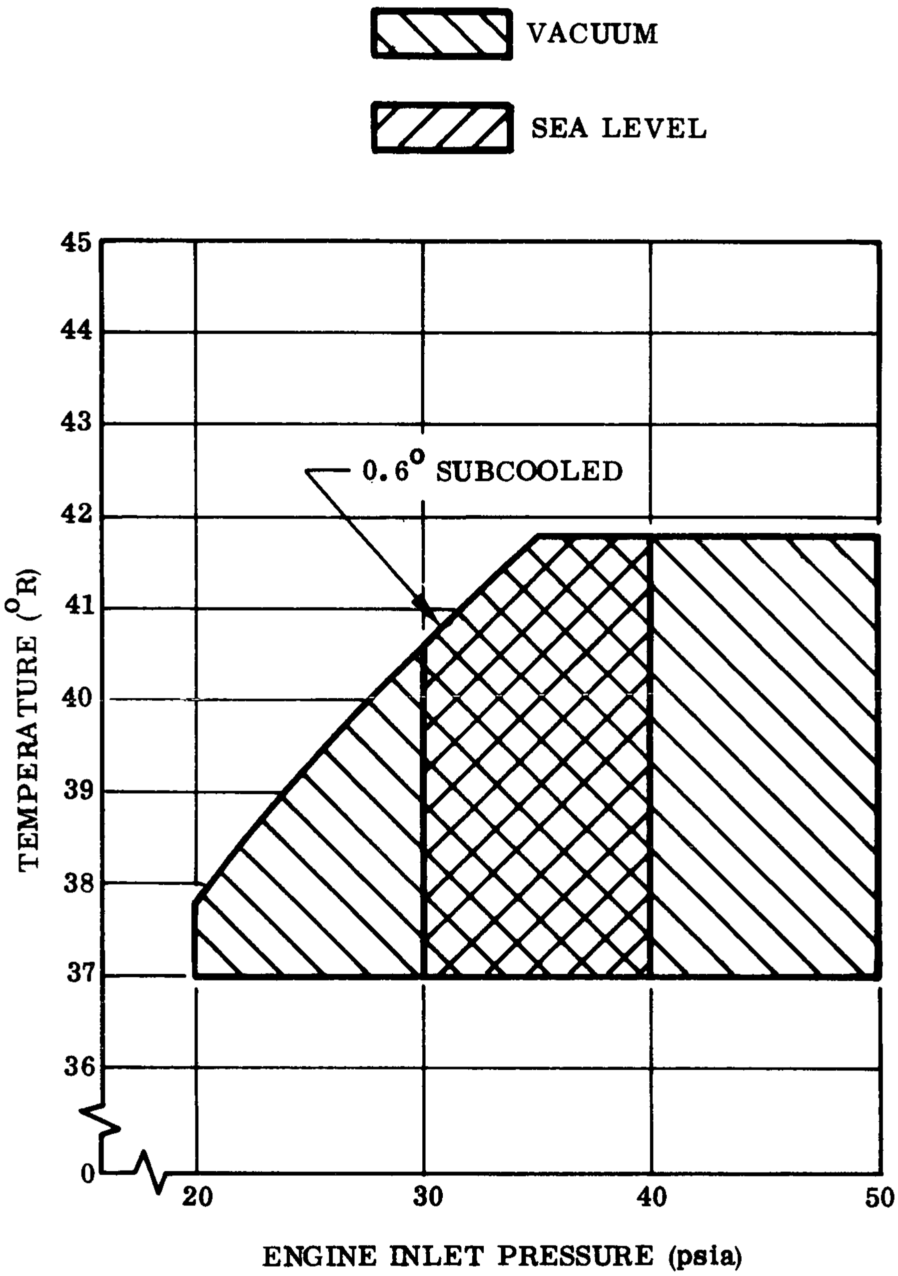


Fig. 5.2-2b Prestart Propellant Condition — Fuel

The Net Positive Suction Head requirements are presented in Figure 5.2-3 for continuous operation. It may be noted that the allowable inlet temperature ranges remain approximately the same, and the inlet total pressure requirements for liquid oxygen are increased.

The engine operating fluid cleanliness limits are presented in Table 5.2-5.

In addition to the ICD information, engine contractor data regarding engine bleed is presented in Figure 5.2-4 and 5.2-5.

These data are based upon the assumption that engine bleed will be at a constant flowrate and temperature.

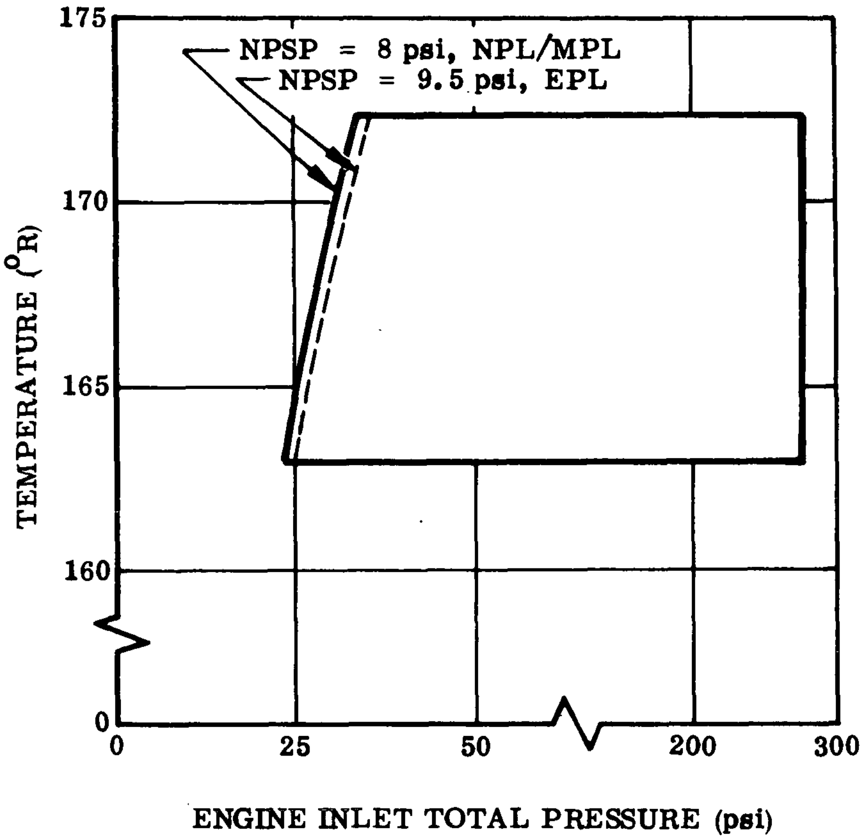
5.2.2.2 Orbit Injection Propellant Supply System Requirements. The Orbit Injection Propellant Supply requirements are presented in Table 5.2-6. There is a significant range of propellant quantities based upon the Phase B and Alternate Concept Study results. A typical duty cycle for the Orbit Injection Propellant Supply is presented in Table 5.2-7.

5.2.3 Attitude Control Propulsion Supply

The Attitude Control Propulsion System (ACPS) requirements are presented in Table 5.2-8. These requirements are based upon 2100 lb thrusters and a maximum flowrate associated with firing six thrusters simultaneously.

A typical Attitude Control Propulsion System duty cycle was constructed for the third revolution rendezvous mission. This is presented in Table 5.2-9.

NOTE:
VALVES REFERENCED
TO Y-Z PLANE



POWER LEVEL

EPL = EMERGENCY
MPL = MINIMUM
NPL = NORMAL

Fig. 5.2-3a Engine Propellant Inlet Conditions (Mainstage Operation) – Oxidizer

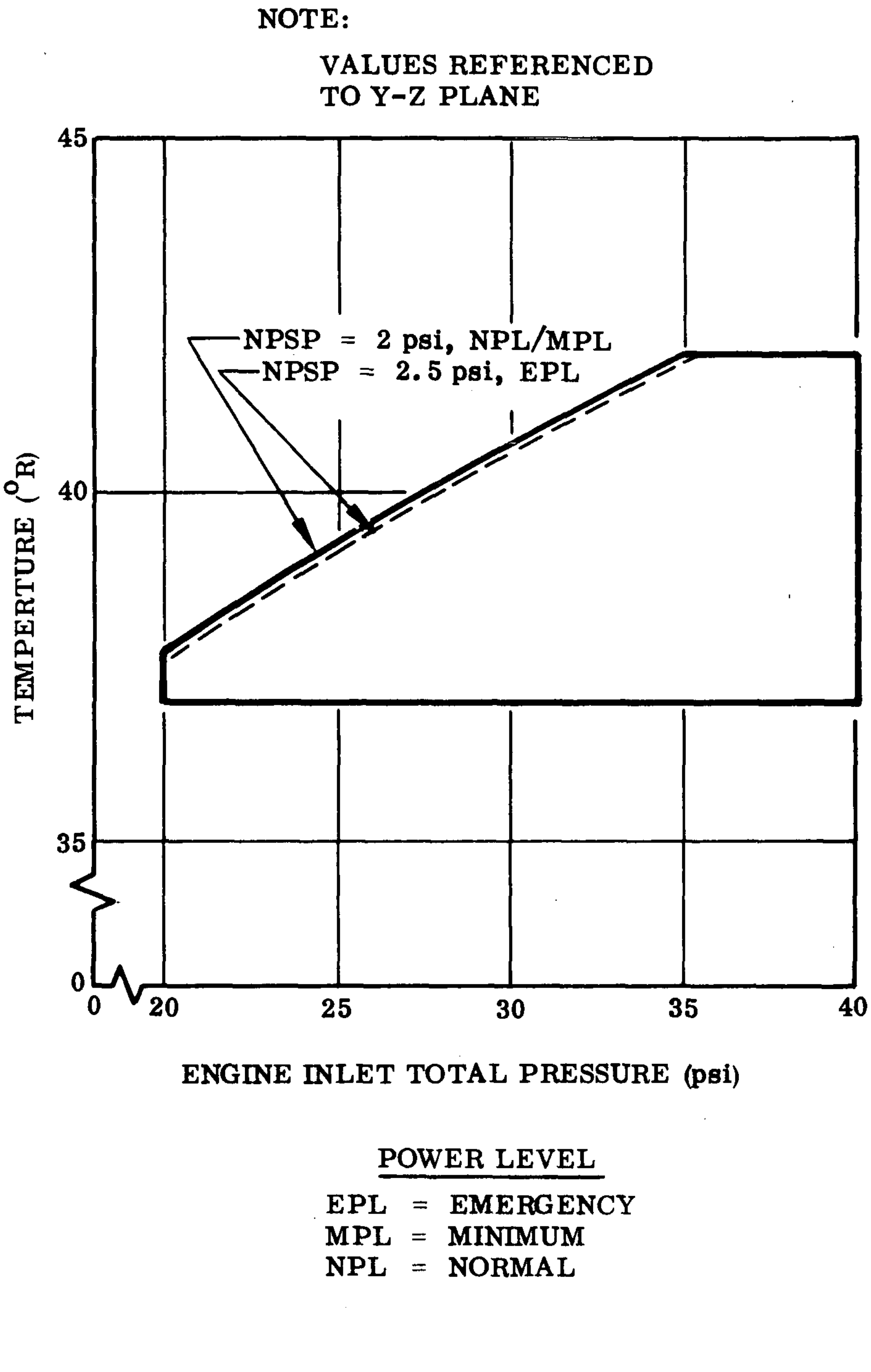


Fig. 5.2-3b Engine Propellant Inlet Conditions (Mainstage Operation) – Fuel

Table 5.2-5

ENGINE OPERATING FLUID CLEANLINESS LIMITS

Type	Maximum Particle Size, or Requirement [1]		Remarks
	Particle Size (x), Microns	Particles Allowable (No.)	
GN_2, [2] MIL-P-27401	$x \leq 30$ $30 < x \leq 100$ $x > 100$	No limit 25 0	
Helium, [2] MSFC-SPEC-364 or MIL-P-27407	$x \leq 30$ $30 < x \leq 100$ $x > 100$	No limit 25 0	
Liquid Oxygen, [3] MIL-P-25508	$x \leq 100$ $100 < x \leq 200$ $200 < x \leq 250$ $x > 250$	No limit 1000 500 0	Acetylene content shall be no larger than 1.55 ppm, soluble hydrocarbon shall not exceed 75 ppm, the purity not to be less than 99.2 percent, and the particulate content of the oxygen must not be limited by the total weight.
Liquid Hydrogen, [3] MIL-P-27201	$x \leq 100$ $100 < x \leq 200$ $200 < x \leq 250$ $x > 250$	No limit 1000 500 0	
Hydraulic Fluid MIL-H-5606	Values specified in MSFC-PROC-166	Values specified in MSFC-PROC-166	

NOTES:

[1] Cleanliness limits specified are the maximum allowable at the engine-to-vehicle interface.

[2] Maximum number of particles based on a 30 standard cubic foot sample.

[3] Maximum number of particles based on a 100 ml sample.

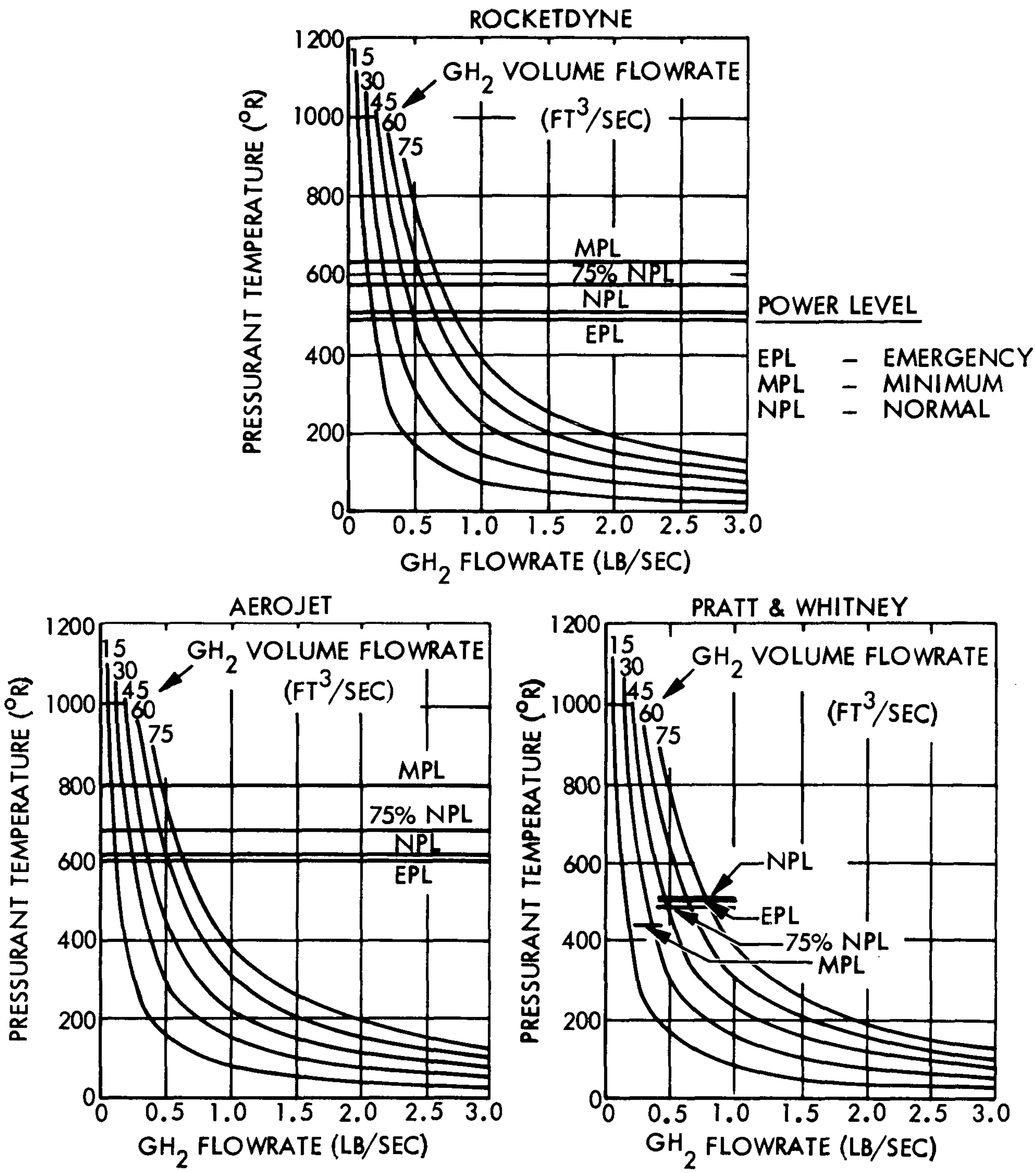


Fig. 5.2-4 Volumetric Flowrate Requirements Compatibility With Engine Pressurant Supply

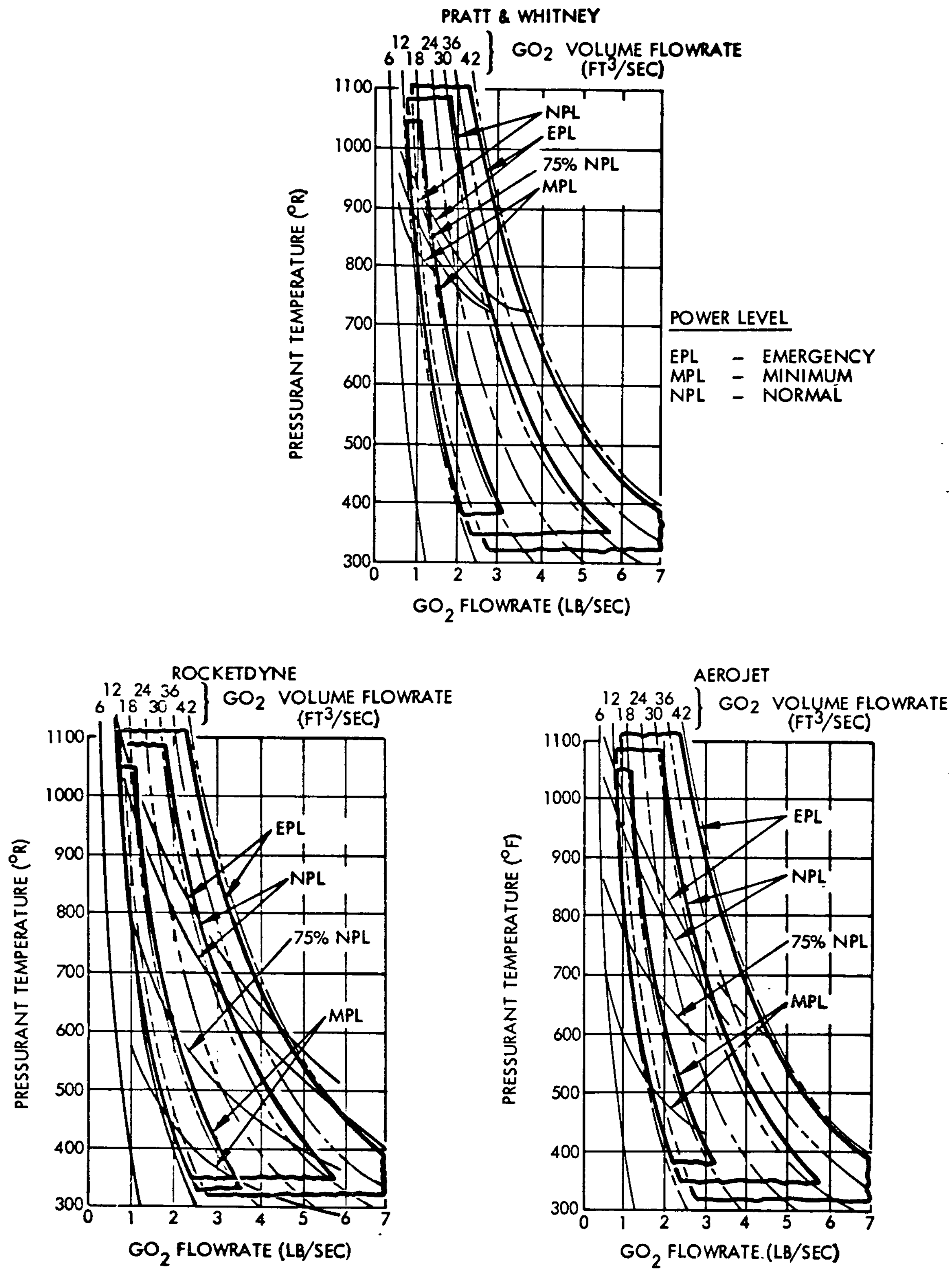


Fig. 5.2-5 Volumetric Flowrate Requirements Compatibility With Engine Heat Exchanger Designs

Table 5.2-6

ORBIT INJECTION PROPELLANT SUPPLY SYSTEM
(Based on a Two-engine Orbiter)

		O_2	H_2	Source Reference
Propellant Quantity	Min Max	360,000 lb 532,000 lb	60,000 lb 89,000 lb	5-1, 5-4, 5-6, 5-7
Propellant Flow Rate	Min Max-Total Max-per engine	593 lb/sec 2374 lb/sec 1294 lb/sec	99 lb/sec 396 lb/sec 216 lb/sec	5-12
Supply System Outlet Pressure (ΔP Above Vapor Pressure)	Nom Max	8 psi 9.5 psi	2 psi 2.5 psi	5-12
Supply System Outlet Temperature		Subcooled liquid		5-12
Mixture Ratio (O/F)	Min Nom Max	5.5:1 6.0:1 ±2% 6.5:1		5-12
Life:				
Operating	Total Per Flight Flights	10 hr Approx. 4-min burn 100		5-11 5-7 5-11
Nonoperating	Total	10 yr		5-11

Table 5.2-7

ORBIT INJECTION PROPELLANT SUPPLY SYSTEM DUTY CYCLE

Event	Mission Time hr:min:sec	Event Δt hr:min:sec	ΔW_{O_2} (lb)	ΔW_{H_2} (lb)	ΔW_{P1} (lb)
Chilldown and slow fill LO_2	-01:47:00	00:17:00	26,600	–	26,600
Chilldown and slow fill LH_2	-01:40:00	00:05:00	–	4,450	[illegible]1,050
Fast fill LH_2	-01:35:00	00:13:00	–	80,100	111,150
Fast fill LO_2	-01:30:00	00:17:00	478,800	–	289,950
Slow fill & top off LH_2	-01:22:00	00:10:00	–	4,450	594,400
Slow fill & top off LO_2	-01:13:00	00:10:00	26,600	–	621,000
Replenish LH_2	-01:12:00	01:10:00	–	AR	621,000
Replenish LO_2	-01:03:00	01:01:00	AR	–	621,000
Disconnect LO_2 & LH_2 fill lines	-00:02:00	00:01:00	–	–	621,000
Launch	00:00:00	–	–	–	621,000
Staging	00:03:16	00:00:10	–	–	621,000
Rocket Engine Operation	00:03:26	00:03:12			
3g Limitation	00:06:38	00:00:44	518,149*	86,358*	
Rocket Engine Shutdown	00:07:22	–			16,493

*Propellant required for nominal I_{sp}

Table 5.2-8

ATTITUDE CONTROL PROPELLANT SUPPLY SYSTEM REQUIREMENTS

		O_2	H_2	Source Reference
Propellant Quantity	Min Max	2000 lb 6900 lb	500 lb 2150 lb	5-1, 5-4 5-13
Propellant Flow Rate	Min Max	1.5 lb/sec 26.1 lb/sec	0.4 lb/sec 7.1 lb/sec	5-1, 5-4, 5-6, 5-13, 5-14
Supply System Outlet Pressure	High Pressure Low Pressure	300 to 500 psia 20 to 45 psia		5-1, 5-4 5-13, 5-14
Supply System Outlet Temperature (°R)	Min Max	200 500		5-1, 5-4 5-13, 5-14
Mixture Ratio (O/F)	Min Max	3.2:1 4.5:1		5-1, 5-4 5-13, 5-14
Life:				
Operating	Total Per Flight Flights Duty Cycle	TBD TBD 100 TBD		— — 5-11 —
Nonoperating	Total Orbital/Flight	10 yr 7 dy		5-11 5-11

f

Table 5.2-9

ATTITUDE CONTROL PROPULSION SYSTEM DUTY CYCLE
– THIRD REVOLUTION RENDEZVOUS

Mission Elapsed Time (hr:min:sec)	ACPS Event	Event t (Min)	Propellant W_p Min	Propellant W_p Max	Consumption Total (lb) Min	Consumption Total (lb) Max
00:00:00	Launch	-	-	-	-	-
00:07:22	Maintain attitude-damp ME cutoff transients	1.0	1.2	1.2	1.2	1.2
00:08:34	Maneuver to local horizontal, impart orbital rate	3.0	63.8	63.8	65.0	65.0
00:11:34	LC, hold ±5° D.B.	27.65	0.1	0.1	65.1	65.1
00:39:15	Maneuver for OMPS burn, hold ±0.5° D.B.	10.0	13.0	13.0	78.1	78.1
00:49:15	Roll control - OMPS burn	3.0	10.3	10.3	88.4	88.4
00:52:15	Maneuver to local horiz., impart orbital rate, hold ±5° D.B.	32.5	1.0	1.0	89.4	89.4
01:24:47	Maneuver for OMPS burn, hold ±0.5° D.B.	10.0	0.9	0.9	90.3	90.3
01:34:47	Roll control - OMPS burn	2.0	8.1	8.1	98.4	98.4
01:36:47	Maneuver to local horiz., impart orbital rate, hold ±5° D.B.	35.0	0.9	0.9	99.3	99.3
02:11:45	Maneuver for OMPS burn, hold ±0.5° D.B.	10.0	1.0	1.0	100.3	100.3
02:21:45	Roll control - OMPS burn	0.3	1.0	1.0	101.3	101.3
02:22:03	Maneuver to LOS attitude	3.0	51.6	51.6	152.9	152.9
02:25:03	LC, hold ±5° D.B.	31.7	0.1	0.1	153.0	153.0
02:56:45	Maneuver to burn attitude, hold ±0.5° D.B.	10.0	51.1	51.1	204.1	204.1

Table 5.2-9 (cont'd)

Mission Elapsed Time (hr:min:sec)	ACPS Event	Event t_e (Min)	Propellant W_p		Consumption Total (lb)	
			Min	Max	Min	Max
03:06:45	Dispersion burn, ΔV = 0-25 fps	0.6	0	540	204.1	744.1
03:07:21	Maneuver to LOS attitude, hold $\pm 5^\circ$ D.B.	33.6	51.1	51.1	255.2	795.2
03:40:56	Maneuver to burn attitude, hold $\pm 0.5^\circ$ D.B.	10.0	51.1	51.1	306.3	846.3
03:50:56	Roll control - OMPS burn	0.3	0.6	0.6	306.9	846.9
03:51:14	Maneuver to LOS attitude, hold $\pm 5^\circ$ D.B.	9.7	51.0	51.0	357.9	897.9
04:00:56	Maneuver to burn attitude, hold $\pm 0.5^\circ$ D.B.	2.0	51.0	51.0	408.9	948.9
04:02:56	MCC - 1 burn, ΔV = 0-36 fps	0.7	0	774.0	408.9	1722.9
04:03:38	Maneuver to LOS attitude, hold $\pm 5^\circ$ D.B.	7.3	51.0	510	459.9	1773.9
04:10:56	Maneuver to burn attitude, hold $\pm 0.5^\circ$ D.B.	2.0	51.0	51.0	510.9	1824.9
04:12:56	MCC - 2 burn, ΔV = 9-19 fps	0.3	0	407.0	510.9	2231.9
04:13:14	Maneuver to LOS attitude, hold $\pm 5^\circ$ D.B.	9.9	51.0	51.0	561.9	2282.9
04:23:06	Maneuver to burn attitude, hold $\pm 0.5^\circ$ D.B.	2.0	51.0	51.0	612.9	2333.9
04:25:06	Braking, ΔV = 10 fps	1.7	216.0	216.0	828.9	2549.9
04:26:46	Braking, ΔV = 13 fps	1.3	278.0	278.0	1106.9	2827.9
04:28:01	Braking, ΔV = 12 fps	1.5	258.0	258.0	1364.9	3085.9
04:29:31	Braking, ΔV = 5 fps	1.7	107.0	107.0	1471.9	3192.9
04:31:11	Braking, ΔV = 5 fps	2.0	107.0	107.0	1578.9	3299.9
04:33:11	Station keeping, hold $\pm 0.5^\circ$ D.B., multi-axis transfer, ΔV = 1-10 fps multi-axis attitude, ΔV = 0-10 fps	22.9	0.4	432.4	1579.3	3732.3

Table 5.2-9 (cont'd)

Mission Elapsed Time (hr:min:sec)	ACPS Event	Event t (Min)	Propellant W_p Min	Propellant W_p Max	Consumption Total (lb) Min	Consumption Total (lb) Max
04:56:06	Docking maneuvers, hold ±0.5° D.B., multi-axis transfer, ΔV = 0-10 fps, multi-axis attitude ΔV = 0-10 fps	10.0	0.2	432.2	1595.5	4164.5
05:06:06	Docked to space station	-	-	-	1579.5	4164.5
-	Passive mode	-	-	-	1579.5	4164.5
163:34:00	Undock - ΔV = 0.5 fps hold ±0.5° D.B.	0.1	11.0	11.0	1590.5	4175.5
163:34:06	Separation maneuver, ΔV = 10 fps, hold ±0.5° D.B.	0.3	216.0	216.0	1806.5	4391.5
163:34:24	Attitude hold ±20° D.B.	159.6	0.1	0.1	1806.6	4391.6
166:14:00	Maneuver to local horizontal, impart orbital rate, hold ±5° D.B.	10.0	63.0	63.0	1869.6	4454.6
166:24:00	Maneuver for OMPS burn, hold ±0.5° D.B.	10.0	36.5	36.5	1906.1	4491.1
166:34:00	Roll control - OMPS retroburn	4.0	14.4	14.4	1920.5	4505.5
166:38:00	Maneuver to entry attitude, hold ±0.5° D.B.	28.0	63.5	63.5	1984.0	4569
167:36:00	Attitude maneuvers as required, ΔV = 25-60 fps, hold ±2° D.B.	AR	510.0	1230.0	2494.0	5799
168:00:00	Land					

5.2.4 Auxiliary Power Unit Reactant Supply

The Auxiliary Power Unit requirements are naturally highly dependent upon the vehicle configuration, the power profile, and the number of APU's in the vehicle. The characteristics of the Auxiliary Power Units which were used in the study are presented in Appendix A. The Phase B requirements resulted in APU sizes from 130 to 850 horsepower, with three of four units per orbiter. The resulting range of requirements are presented in Table 5.2-10. An APU duty cycle is presented in Fig. 5.2-11.

5.2.5 Fuel Cell Supply

The fuel cell reactant supply requirements were obtained from the Phase B studies. The system was assumed to consist of four fuel cells, each capable of operating at 7KW max., continuous load/10KW peak load, and at 1.5 KW minimum power level. The fuel cell reactant requirements are presented in Table 5.2-12. A typical fuel cell reactant supply duty cycle is presented in Table 5.2-13.

5.2.6 Life Support

The system requirements for each major phase of the nominal mission are presented on Table 5.2-14. The minimum conditions are based on an assumed crew of two astronauts (no cargo handlers) functioning at low metabolic rates. Leakage is assumed at 2.0 lb/day. During the docked phase, it is presumed that the crew remains in the space station. For the nominal condition, the crew consists of four, including two cargo handlers. During the docked portion of the mission, two men are presumed to remain in the shuttle. Metabolic rates are nominal for each phase of the mission. Cabin leakage rate is 5.0 lb/day. No cabin repressurization is assumed. For the maximum condition, a four-man crew operating at a high metabolic level is considered. During the docked portion of the mission, the men remain within the vehicle. This assumption also satisfies alternate missions which are independent of the space station. Cabin leakage is 9.0 lb/day.

Table 5.2-10

AUXILIARY POWER UNITS REACTANT SUPPLY SYSTEM REQUIREMENTS

			O_2 Min	O_2 Max	H_2 Min	H_2 Max	Source Reference
Reactant Quantity (lb):			100	500	100	525	5-1, 5-15
Reactant Flowrate (lb/sec):			0.02	0.25	0.02	0.29	
Reactant Mixture Ratio (O/F)		Min Nom Max	0.4 - 0.9				5-1
Life:							
	Operating	Total	Nom - 250 hr Max - TBD				5-15 -
		Cycle	100 missions				5-11
		Per Flight	TBD				-
		Starts/Stops	Min - 1/flight Nom - 2/flight Max - TBD				5-1 5-15 -
		Duty Cycle	Min - TBD Nom - see below Max - TBD				- 5-15 -
	Nonoperating	Total	10 yr				5-11
		Orbital	7 dy/flight				5-11

Table 5.2-11

AUXILIARY POWER UNIT DUTY CYCLE

Mission Phase	Time Begin (sec)	Duration (sec)	APU Reactant (lb)
Prelaunch	1.0	1:0	105
Ascent	0	0:48	88
Rendezvous	157:32 162:00	4:28 2:30	9
Entry	166:00	0:30	96
Descent	166:36	1:15	400 130
Landing	167:45	0:15	117
Reserve			77
Total			1022

Table 5.2-12

FUEL CELL REACTANT SUPPLY REQUIREMENTS

	O_2		H_2		Source Reference
	Min	Max	Min	Max	
Reactant Quantity (lb)	730	1450	90	175	5-1, 5-4 5-15
Reactant Flowrates (lb/hr):					
For the system	2.8	19.0	0.35	2.30	5-1, 5-4 5-15
For an individual fuel cell	1.13	9.5	0.14	1.15	5-1, 5-4 5-15
Reactant Outlet Pressure (psia)	2.0	200	20	200	5-1, 5-15, 5-16, 5-17
Reactant Outlet Temperature (°F)	-200	+160	-200	+160	5-15
Life: Total 10 yr Operating Minimum 16,800 hr Starts/Stops 500 Missions 100					

Table 5.2-13

FUEL CELL REACTANT SUPPLY DUTY CYCLE

MISSION PHASE	FLOW RATES (lb/hr)				QUANTITY (lb)				DURATION (hrs)
	O_2		H_2		O_2		H_2		
	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	
Prelaunch	5.36	9.51	0.665	1.15	9.4	14.3	1.2	1.7	1.5
Ascent	5.39	10.30	0.668	1.24	0.5	1.0	0.06	0.12	0.12
Orbit/Phasing	4.30	12.20	0.533	1.47	85.5	237.8	10.6	28.8	20.0
Rendezvous/ Dock	5.80	12.10	0.720	1.46	17.4	35.6	2.2	4.3	3.0
Orbit Standby	4.08	6.50	0.506	0.78	517.7	813.1	64.3	98.3	121.38
Orbit Phasing	4.30	12.38	0.533	1.50	94.6	197.8	11.8	23.9	22.0
Entry	6.35	9.33	0.787	1.13	2.6	12.0	0.3	1.5	1.0 to 1.5
Landing	6.35	8.95	0.787	1.08	3.8	8.0	0.5	1.0	0.75
Total Reactants (lb)					731.5	1319.6	90.96	159.6	

1) Short term max rates are: 19.0 lb/hr O_2 and 2.3 lb/hr H_2 (20 KW)

2) Min and Max rates for a single fuel cell are:

	O_2	H_2
Min	1.13 lb/hr	0.14 lb/hr
Max	9.51 lb/hr	1.15 lb/hr

Table 5.2-14

ECLSS OXYGEN AND NITROGEN SUPPLY REQUIREMENTS

HIGH CROSSRANGE VEHICLE

Mission Phase	Duration (hr)	Oxygen (lb)			Nitrogen (lb)			Source Reference
		Min	Nom	Max	Min	Nom	Max	
Prelaunch	2.0	0.28	0.63	0.75	0	0.04	0.08	5-1, 5-18, 5-19
Ascent	0.1	0.02	0.04	0.06	0	0.01	0.04	5-1, 5-18, 5-19
Orbit/Phasing Rendezvous/ Dock	25.5	4.03	8.91	11.32	1.67	4.18	7.50	5-1, 5-18, 5-19
Orbit Operations	126.2	2.47	26.0	56.35	8.34	20.83	37.54	5-1, 5-18, 5-19
Orbit Phasing	13.9	2.19	5.21	6.17	0.91	2.28	4.11	5-1, 5-18, 5-19
Entry	1.6	0.26	0.59	0.74	0.11	0.27	0.49	5-1, 5-18, 5-19
Landing	0.5	0.06	0.14	0.17	0	0	0	5-1, 5-18, 5-19
Totals		9.31	41.52	75.56	11.03	27.61	49.76	5-1, 5-18, 5-19

Oxygen consumption consists of leakage and metabolic requirements. Nitrogen consumption consists of leakage make-up requirements only. The following usages applied as described in the text were used to size the system requirements.

	O_2 Metabolic (lb/day)	Leakage (lb/day)
Min	1.69	2.0
Nom	1.84	5.0
Max	2.20	9.0

The supply pressure presented in Table 5.2-14 is sufficient to provide a 14.7 psia atmosphere, water tank pressurization, and accomodate line losses. This pressure, however, would not be sufficient for umbilical EVA (which requires 100 psia) or for PLSS backpack recharging (which requires 1500 psia). It also should be noted that the allowable gas temperature range (-40 to +150°F) does not imply that this is an acceptable range for cabin temperature or for the conditioning heat exchanger design. If the gas were introduced to the cabin within this band, at the small rates involved, it would impose a negligible load on the thermal control system as mixed with the large cabin atmosphere quantity.

5.2.7 Purging, Inerting, and Pneumatic Supply

The Purging, Inerting, and Pneumatic Supply requirements were derived from the following:

- <u>Helium Requirements</u> (Possible)
  - Main engine pneumatic and purging
  - RL-10 pneumatic and purging
  - Pneumatic valves
  - Hydrogen tank insulation purging

- <u>Nitrogen Requirements</u> (Possible)
  - Hydrogen tank inerting
  - Hydrogen purging (leakage regions)
  - Oxygen tank insulation purging
  - Airbreathing fuel oxygen removal and tank inerting

The requirements are very dependent upon the approaches and conditions assumed. The analyses determining the requirements and the results are presented in Section 9.7.

Table 5.2-15

ECLSS OXYGEN AND NITROGEN INTERFACE REQUIREMENTS

		O_2	N_2	Source Reference
Cryogen Flow Rate	Normal Max	15 lb/hr	7.5 lb/hr	
Cryogenic Interface:				
Outlet Pressure (Regulated)		50 ± 6 psia	60 ± 5 psia	1
Outlet Temperature, °F		-40 to +150		10
Purity	Min Nom	TBD B (Per NASA MSFC Spec. 356A and 399A)		- 1
Life:				
Total	10 yr			
Operating	16,800 hr			
Continuous	168 hr			
Missions	100			

Section 6

RESULTS OF SUBSYSTEM TRADEOFF STUDIES

The subsystem tradeoff studies were utilized to accomplish several of the study major outputs:

- Comparison of individual subsystems
- Provision of information necessary for the selection of integrated systems
- Sensitivities of the subsystems to criteria, requirements, and design variables
- Sensitivity of the subsystems to technology status

The examination of the individual subsystems contributed significantly to the selection of the approaches to integrated systems. The tradeoff studies indicated the most attractive subsystem concepts. The detailed subsystem tradeoff studies are presented in Section 9.

6.1 GENERAL APPROACH

The general approach employed in analyzing each of the individual subsystems is presented in Figure 6.1-1:

(1) Criteria and requirements were established for each subsystem.

(2) Candidate subsystem matrices were established.

(3) The detailed subsystem analyses began with an evaluation of the composition and arrangements through schematics and physical locations in the vehicles.

(4) Operational modes and duty cycles were established.

(5) The structural design studies were principally parametric evaluations.

(6) The detailed analyses heavily involved thermodynamic and fluid dynamic analyses.

(7) Expendable evaluations included gas and liquid residuals and vent losses.

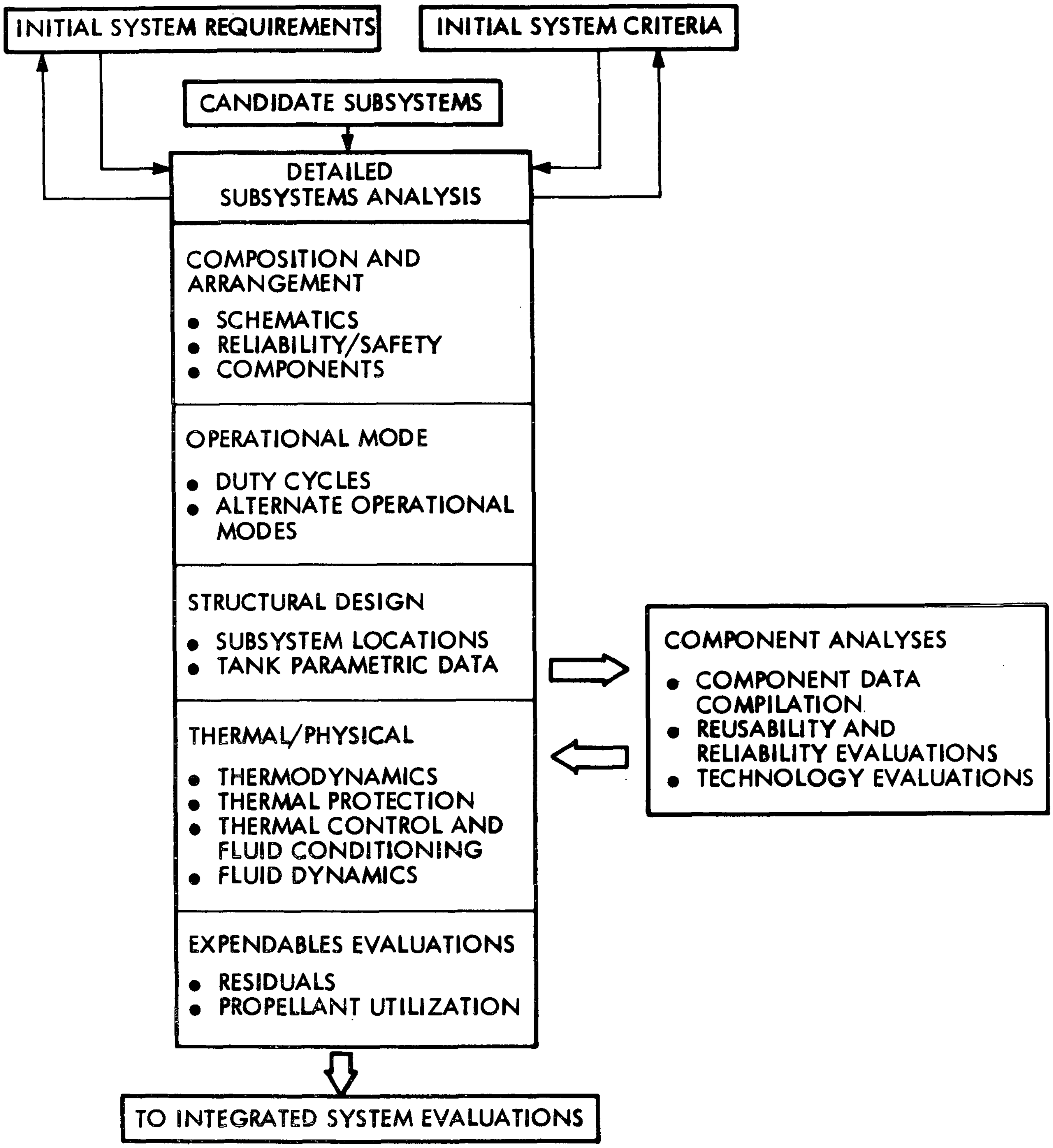


Fig. 6.1-1 Concept Evaluation

6.2 ORBIT MANEUVERING PROPELLANT SUPPLY

The Orbit Maneuvering Propellant Supply subsystems evaluations involved a number of issues relative to the concepts. A major portion of the tradeoff studies were devoted to examining these concept issues and determining the advantages and disadvantages. The major differences between the OMPS subsystem arrangements are established by:

- Vehicle Configuration Constraints

  The vehicle configurations dictated the number of tanks to comply with available space.

  (a) Single Tanks

  (b) Dual Tanks

  The dual tanks may have either cascaded flow or noncascaded flow.

- Location of Pumps

  The propellant pumps location was an important issue in the subsystem evaluations which also reflected into the integrated system.

  (a) Pump-at-engine

  The pumps are integral parts of the engine as in the RL-10.

  (b) Pump-at-tank

  The pumps are separated from the engine and located at the propellant tanks.

- Start Tanks

  Start tanks have limited application to individual subsystems, but were examined in the studies.

- Type of Pressurization

  The type of pressurization has considerable impact upon the overall system. Propellant acquisition approaches are significantly affected.

(a) Helium Pressurization, separately stored helium.

(b) GO_2/GH_2 Pressurization

The prepressurization gases may be separately stored or idle start mode can be employed. Pressurization gases during engine operation are supplied from engine bleed.

- Extent of the Use of Vacuum Jacketing

  Vacuum jacketing has a potential significant effect on the subsystem approach and operation.

The principle candidates have been displayed to provide the advantages and disadvantages of the approaches and comparisons between approaches. The information is presented in Tables 6.2-1 through 6.2-7.

Results of Concept Comparisons

Comparisons of the effects on weight were considered to be major points of comparison, but other factors were considered. The comparisons indicated:

(1) When the turbopumps are located at the tank (good integration potential), the dry weight and total weight is less than for a conventional pump-at-engine such as the RL-10 engine.

(2) The pump-at-tank location is relatively insensitive to the number of propellant feedline losses. For the pump-at-engine, the total system weight keeps increasing as the number of feedline losses increases.

(3) Pressurization with helium results in lighter weight subsystems than pressurization with GO_2/GH_2. This is principally the result of the requirement in a nonintegrated system that the GO_2/GH_2 prepressurant be stored in gas storage tanks specifically for this application.

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The use of an inflight refill technique for GO_2/GH_2 prepressurant gas storage tanks to reduce this penalty was eliminated by the large quantities that must be stored and the high-flowrates that would be required to refill during a short OMPS burn (e.g., when the LO_2 propellant tank has been depleted so only the retropropellant is left, prepressurant GO_2 will range from approximately 50-to-100 lb depending upon ullage pressure requirements). Since some OMPS engine operations are in the order of 12-to-28 sec, resupply flowrates could range from approximately 4-to-8 lb per sec. Because the rocket engine also is supplying pressurization gas during the firing/expulsion, the combined gas-bleed requirements are deemed beyond the capacity of the engine, and the refill technique was eliminated.

(4) Vacuum jacketed tanks and lines result in higher overall subsystem weights than do non-jacketed subsystems. However, the insulation and other thermal control provisions are protected and result in better reusable subsystems.

(5) If dual tanks are required in the vehicles, the cascade tank approach is approximately the same weight as the noncascaded approach. A disadvantage identified was that a more complex pressurization system is required to achieve these comparable weights. Helium is employed in the downstream tank and GO_2/GH_2 in the upstream tanks. An advantage to this approach is that only one tank requires a propellant acquisition system for engine start.

(6) Start tanks for nonintegrated systems appear to provide no advantages and increase the complexity of the systems.

Results of Comparison of Optimum Conditions

As the tradeoff studies were performed, the optimum designs and operating conditions were established. A summary of optimum conditions for all of the cases, except the cascade and start tanks, is shown in Table 6.2-8. Several observations are possible from the data:

(1) The insensitivity of the total system weight to the number of propellant losses, for the pump-at-tank concept, is attributed to constant ullage pressure and feedline diameters as a function of the number of propellant losses.

(2) For the pump-at-engine concept, the optimum configuration results in increasing ullage pressure requirements as the number of propellant losses increases. While feedline diameters were reduced, with a resultant decrease in line and valve weights, this effect was small in comparison to the increased prepressurant requirements due to the increased ullage pressure. Since all of the prepressurant was stored, the storage sphere weight increased considerably as the number of propellant losses increased from 1 to 12.

Configuration	Vacuum-Jacketed Tanks and Lines Number of Dumps			Nonvacuum-Jacketed Tanks and Lines Number of Dumps		
	1	5	12	1	5	12
System Dry Weight (lb)	2,657	2,715	2,812	1,961	2,021	2,112
System Wet Weight (lb)	31,500	31,707	32,079	30,947	31,150	31,507
Advantages:	1. Less complex for one dump case as line childown not required 2. Lighter than comparable system with gaseous propellant pressurization 3. No ground purging of tank insulation required 4. Insulation less susceptible to damage and degradation than nonvacuum-jacketed subsystem during repeated reuses of system 5. Duty cycle does not affect pressurant weights			1. Lighter than comparable vacuum-jacketed system 2. Lighter than comparable system with gaseous propellant pressurization 3. Less dry weight than comparable vacuum-jacketed system 4. Duty cycle does not affect pressurant weights		
Disadvantages:	1. Heavier than comparable nonvacuum-jacketed system 2. Requires helium, which is inconsistent with goal to minimize shuttle helium 3. May require periodic annular region vacuum check and evacuation of vacuum shells			1. Line childown required for all cases evaluated 2. Requires helium, which is inconsistent with goal to minimize shuttle helium 3. Requires ground and reentry purging of tank insulation 4. More complex than comparable vacuum-jacketed system		

Table 6.2-1
SINGLE TANK – PUMP-AT-ENGINE – GHe PRESSURIZATION

FOLDOUT FRAME 1

FOLDOUT FRAME 2

Configuration	Vacuum-Jacketed Tanks and Lines Number of Dumps			Nonvacuum-Jacketed Tanks and Lines Number of Dumps		
	1	5	12	1	5	12
System Dry Weight (lb)	2,407	2,403	2,408	1,665	1,663	1,665
System Wet Weight (lb)	31,082	31,070	31,211	30,410	30,401	30,538
Advantages:	1. Relatively insensitive to number of dumps 2. No ground purging of tanks required 3. Duty cycle does not affect pressurant weights 4. Insulation less susceptible to damage and degradation than nonvacuum-jacketed subsystem during repeated reuses of system			1. Lowest dry and wet weight of all systems evaluated 2. Insensitive to number of dumps 3. Duty cycle does not affect pressurant weights		
Disadvantages:	1. Heavier than comparable nonvacuum-jacketed system 2. Requires helium, which is inconsistent with goal to minimize shuttle helium 3. May require periodic annular region vacuum check and evacuation of vacuum shells			1. Line childown required for all cases evaluated 2. Requires helium, which is inconsistent with goal to minimize shuttle helium 3. Requires ground and reentry purging of tank insulation 4. More complex than comparable vacuum-jacketed system		

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Table 6.2-2
SINGLE TANK – PUMP-AT-TANK – GHe PRESSURIZATION

FOLDOUT FRAME 2

FOLDOUT FRAME 1

Configuration	Vacuum-Jacketed Tanks and Lines Number of Dumps			Nonvacuum-Jacketed Tanks and Lines Number of Dumps		
	1	5	12	1	5	12
System Dry Weight (lb)	3,249	3,423	3,676	2,517	2,689	2,915
System Wet Weight (lb)	32,357	32,825	33,542	31,716	32,182	32,871
Advantages:	1. Does not require helium 2. No purging at tank insulation required 3. Insulation less susceptible to damage and degradation than nonvacuum jacketed subsystem during repeated reuses of system 4. Both dry and wet weight are sensitive to the number of dumps			1. Does not require helium 2. Lighter than comparable vacuum-jacketed system 3. Both dry and wet weight are sensitive to the number of dumps		
Disadvantages:	1. Highest sensitivity of all systems evaluated to number of dumps 2. Highest dry and wet weight of all systems for comparable number of dumps 3. Dry and wet weight heavier than comparable helium pressurized system 4. Duty cycle affects pressurant requirements 5. May require periodic annular region vacuum check and evacuation of vacuum shells			1. Line chilldown required for all cases evaluated 2. Requires purging of tank and line insulation during groundhold and reentry 3. High sensitivity to number of dumps 4. Duty cycle affects pressurant requirements		

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Table 6.2-3
SINGLE TANK – PUMP-AT-ENGINE – GO_2/GH_2 PRESSURIZATION

FOLDOUT FRAME 1

FOLDOUT FRAME 2

Configuration	Vacuum-Jacketed Tanks and Lines Number of Dumps			Nonvacuum-Jacketed Tanks and Lines Number of Dumps		
	1	5	12	1	5	12
System Dry Weight (lb)	2,828	2,831	2,836	2,146	2,138	2,145
System Wet Weight (lb)	31,550	31,545	31,684	30,910	30,894	31,035
Advantages:	1. Does not require helium 2. Relatively insensitive to number of dumps 3. Does not require insulation purging 4. Dry weight 400-to-800 lb lighter than comparable pump-at-engine system 5. Wet weight 800-to-1850 lb lighter than comparable pump-at-engine system 6. Insulation less susceptible to damage and degradation than nonvacuum-jacketed subsystem			1. Does not require helium 2. Relatively insensitive to number of dumps 3. Dry weight 370-to-770 lb lighter than comparable pump-at-engine system 4. Wet weight 800-to-1850 lb lighter than comparable pump-at-engine system 5. Less dry weight than comparable vacuum-jacketed system		
Disadvantages:	1. Heavier than comparable helium-pressurized system 2. Prepressurant storage tank required and quantity of prepressurized sensitive to collapse factor. (Could eliminate pre-pressurant storage tank by getting pre-pressurant from some other source such as ACPS accumulators) 3. Prepressurizing with hot gases is a potential problem area at zero "g" due to potential collapse if liquid pro-pellant encloses pressurization gas outlet in tank 4. Duty cycle affects pressurant requirements 5. May require periodic annular region vacuum check and evacuation of vacuum shells			1. Same as 1, 2, and 3 for vacuum-jacketed system 2. Requires prelaunch and reentry purging of tank and lines 3. Duty cycle affects pressurant requirements		

FOLDOUT FRAME 1

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Table 6.2-4
SINGLE TANK – PUMP-AT-TANK – GO_2/GH_2 PRESSURIZATION

FOLDOUT FRAME 2

Configuration	Vacuum-Jacketed Tanks and Lines Number of Dumps			Nonvacuum-Jacketed Tanks and Lines Number of Dumps		
	1	5	12	1	5	12
System Dry Weight (lb)	3,097	3,280	3,307	2,267	2,332	2,357
System Wet Weight (lb)	31,989	32,355	32,955	31,269	31,516	32,112
Advantages:	1. Does not require insulation purging 2. Less complex for one dump case as line chilldown not required 3. Insulation less susceptible to damage and degradation than nonvacuum-jacketed subsystem during repeated reuses of system 4. May package better in vehicle 5. Duty cycle does not affect pressurant weights			1. Lighter than comparable vacuum-jacketed system 2. May package better in vehicle 3. Duty cycle does not affect pressurant weights		
Disadvantages:	1. Dry weight approximately 500 lb heavier than comparable single-tank system for all cases evaluated 2. Wet weight a minimum of 500 lb heavier than comparable single-tank system and differential increases as the number of dumps increases 3. Requires, helium, which is inconsistent with goal to minimize shuttle helium 4. May require periodic annular region vacuum check and evacuation of vacuum shells 5. More complex than single-tank system due to larger number of components for the cooling, acquisition, etc. 6. Residuals probably higher than in single-tank system due to potential of draining one tank faster than the other and pull-through causing gas ingestion in the feedline 7. Greater potential for tank heat leaks due to increased surface area and large number of support struts than on single-tank system			1. Dry weight approximately 300 lb heavier than comparable single-tank system for all cases evaluated 2. Wet weight a minimum of 300 lb heavier than single-tank system for 1 and 5 dump cases and increases to approximately 600 lb for the 12 dump case 3. Requires helium, which is inconsistent with goal to minimize shuttle helium 4. Requires ground and reentry purging of tank and line insulation 5. Line chilldown required for all cases evaluated 6. Same as 5, 6, and 7 for vacuum-jacketed case		

Table 6.2-5
DUAL TANKS – PUMP-AT-ENGINE – GHe PRESSURIZATION

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FOLDOUT FRAME 1

FOLDOUT FRAME 2

Configuration	Vacuum-Jacketed Tanks and Lines Number of Dumps		Nonvacuum-Jacketed Tanks and Lines Number of Dumps	
	5	12	5	12
System Dry Weight (lb)	3,273	--	2,604	2,679
System Wet Weight (lb)	32,532	--	31,922	32,292
Advantages:	1. Requires helium in downstream tank only 2. Vacuum-jacketing on downstream tank only 3. Acquisition system simplified, compared to single tank, as only required in downstream tank 4. Duty cycle does not affect pressurant weights		1. Requires helium in downstream tank only 2. Same as 3 for vacuum-jacketed system 3. Duty cycle does not affect pressurant weights	
Disadvantages:	1. Requires helium 2. More complex pressurization system as both helium and engine-bleed gases are used for tank pressurization 3. Dry weight approximately 550 lb heaver than comparable single-tank system 4. Wet weight approximately 800 lb heavier than comparable single-tank system 5. Dry weight approximately the same as a comparable conventional dual-tank system 6. Wet weight approximately 200 lb heavier than a comparable conventional dual-tank system		1. Same as 1 and 2 for vacuum-jacketed system 2. Dry weight approximately 600 lb heavier than comparable single-tank system 3. Wet weight approximately 800 lb heavier than comparable single-tank system 4. Dry weight approximately 300 lb heavier than a comparable conventional dual-tank system 5. Wet weight 400 lb heavier than for a comparable dual-tank system but decreases to approximately 200 lb for 12 dumps 6. Requires ground and reentry purging of tank and line insulation	

Table 6.2-6
CASCADED TANKS – PUMP-AT-ENGINE – GHe PREPRESSURIZATION AND GHe/ENGINE BLEED PRESSURIZATION

FOLDOUT FRAME 1

FOLDOUT FRAME 2

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Table 6.2-7

SINGLE TANK WITH START TANK - PUMP-AT-ENGINE
GO_2/GH_2 PRESSURIZATION

	Configuration One Dump-Nonvacuum-Jacketed Tanks and Lines
System Dry Weight	~ 2,300 lb
System Wet Weight	~ 31,200 lb
Advantages:	1. Simplifies propellant acquisition 2. Reduces helium usage to start tank only 3. Eliminates prepressurization components and function as start tank acts as helium spring 4. Eliminates duty cycle effect on pressurant requirements for a hot gas pressurization system
Disadvantages:	1. Requires ground and reentry purging of tank and line insulation 2. Limits operations to engine burns of 10 seconds or greater 3. Dry weight approximately 350 lb heavier than comparable helium pressurized system 4. Added complexity due to start tank refill during OMPS operation 5. Wet weight approximately 250 lb heavier than comparable helium pressurized system

Table 6.2-8

OMPS SUBSYSTEM CHARACTERISTICS

Case No.	Tank Config	Pump Location	Pressurant	No. of Dumps	Optimum Feedline Diameter (in.)		Ullage Pressure (psia)	
					O_2	H_2	O_2	H_2
1	Single	Engine	GO_2 and GH_2	1 5 12	3 2-1/2 2	3-1/2 3-1/4 3	36.8 45.2 57.6	23.4 23.8 24.2
2	Single	Tank	GO_2 and GH_2	1 5 12	1 1 1	1 1 1	20.0 20.0 20.0	18.0 18.0 18.0
3	Single	Engine	GHe	1 5 12	3 2-1/2 2	3-1/2 3-1/4 3	36.8 47.2 57.6	23.4 23.8 24.2
4	Single	Tank	GHe	1 5 12	1 1 1	1 1 1	20.0 20.0 20.0	18.0 18.0 18.0
5	Dual	Engine	GHe	1 1 12	2/3 2/3 2/3	3/3 3/3 3/3	34.4 34.4 34.4	23.5 23.5 23.5

NOTE: For the dual tank case, feedline diameters signify tank outlet to common point/common point-to-engine inlet.

6.3 ORBIT INJECTION PROPELLANT SUPPLY

The Orbit Injection Propellant Supply (OIPS) system evaluations were related to examination of alternate approaches to subsystem functions rather than the comparison of overall subsystem approaches. The comparison of overall subsystems requires extensive considerations regarding tankage parameters, performance data, and other vehicle peculiar data. The evaluations to be performed were selected through coordination with NASA/MSC and represented issues of interest. The evaluations included:

- Sensitivity of thermodynamic parameters to insulation effectiveness.
- Prepressurization concepts
- Pressurization approaches, which included:
  - (a) Modulated pressurization in which pressurization flow can be controlled in on/off modulation
  - (b) Pressurization with constant flow rate with excess vented.
  - (c) Pressurization of LO_2 tanks by self-pressurization
  - (d) Employment of common vent and pressurization lines.
- Feedline temperature control concepts:
  - (a) Effects of insulation on temperature control
  - (b) Temperature control by circulation
- Feedline pressure losses
- Reentry effects on tank pressure rise.

The pressurization studies made extensive use of the LMSC Asymmetric Propellant Heating Computer Program which considered propellant stratification.

Important pressurization comparisons which resulted from the evaluations are displayed in Tables 6.3-1 and 6.3-2. The significant conclusions derived from the evaluations are:

- Onboard prepressurization from stored helium appears to have definite advantages over prepressurization with helium prior to launch (or onboard prepressurization with propellant gases).
- The pressurization approach may be either constant flow rate or modulated engine bleed, without significant weight penalties.
- The use of a common vent and pressurization line is a satisfactory approach. The vent line size is established by the tank fast fill rates during propellant loading. The resulting line sizes (approximately 6 inches) result in low pressure drops during pressurization flow and relatively low pressure lines are feasible.
- The propellant tank pressurization parameters, such as resulting residuals and required mass flow rates, are relatively insensitive to the thermal conductivity or thickness of the tank insulation.
- Feedline propellant temperature control must be accomplished by circulation at rates requiring pumps. The resulting temperature rises in the feedlines are not very sensitive to the insulation type or thickness.
- If the propellant tank pressures are adjusted to approximately 18 psia in orbit prior to reentry, the heating cycle during reentry will not result in the tank pressures exceeding approximately 28 to 30 psia without venting.

	Ground Subsystem	Onboard Subsystem	
	Helium	Helium	Propellant Gases
System Dry Weight (lb)	NA	310	351
System Wet Weight (lb)	NA	335	368
Advantages	1. No onboard gas storage required	1. Tanks not pressurized to high values during maximum g while on booster 2. Ullage pressure rise from propellant stratification does not result in necessity to vent tanks during ascent 3. Helium has an advantage as an onboard pressurization gas in that it is not sensitive to collapse after pressurization	1. Tanks pressurized to high values during maximum g while on booster 2. Ullage pressure rise from propellant stratification does not result in necessity to vent tanks during ascent
Disadvantages	1. Tanks pressurized during high g loading during ascent on booster 2. Vapor pressure rise from stratification adds to helium partial pressure and the necessity for venting with helium loss may occur 3. If tank pressurization is lost during ascent there are no gases available to pre-pressurize tanks	1. Onboard storage and subsystem required	1. Onboard storage and subsystem required 2. Propellant gas pressurization sensitive to collapse if duty cycle is incorrect

Table 6.3-1
COMPARISON OF PRESSURIZATION CONCEPTS FOR ORBIT INJECTION SUBSYSTEM

FOLDOUT FRAME 1

FOLDOUT FRAME 2

	Modulated Flowrate Pressurization	Constant Flowrate Bleed Pressurization
Residual Gas Weight	685	690
Vented Gas Weight	None	60
Advantages:	1. Normally, vent valve would not function	1. Compatible with high pressure engine design approach
Disadvantages:	1. Modulated flowrate puts additional requirements on engine design	1. Vent valve must operate during engine operation

Table 6.3-2
COMPARISON OF PRESSURIZATION METHODS FOR ORBIT INJECTION SUBSYSTEM

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6.4 ATTITUDE CONTROL PROPELLANT SUPPLY

The Attitude Control Propellant Supply (ACPS) system studies were principally comparisons between Gas/Gas type and Liquid/Liquid type subsystems and various approaches to these subsystems. Gas/Gas Attitude Control Subsystems employ gaseous oxygen/hydrogen in the thrusters. The Gas/Gas ACPS Subsystems may utilize either subcritical storage or supercritical storage. The Liquid/Liquid Attitude Control Subsystems deliver liquid oxygen and liquid or supercritical hydrogen to the thrusters.

The summary of the ACPS subsystems is presented in Table 6.4-1. Weights in this table include the feedlines for distribution to the thrusters. Significant conclusions which were derived from the studies are:

Comparison of Gas/Gas and Liquid/Liquid ACPS

- The comparison of Gas/Gas ACPS and Liquid/Liquid ACPS indicated that for subcritical storage conditions, the dry system weights and the system wet weights overlap considerably. The total range being approximately 1200 lb for dry weights and 900 lb for wet weights.

- For similar methods of providing the pump drive, the system dry weights and wet weights of the Gas/Gas and Liquid/Liquid ACPS are comparable.

- The Liquid/Liquid ACPS is sensitive to the bellows contraction.

- As a general conclusion, the Gas/Gas ACPS and Liquid/Liquid ACPS have comparable subsystem dry weights and wet weights.

Comparison of Subcritical and Supercritical Storage for Gas/Gas ACPS Subsystems

- Supercritical storage of the propellants results in considerably more weight penalty than the subcritical storage.

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Comparison of Methods of Pump Drive

- Electrical motor-driven pumps in subsystems result in higher dry weights. However, considering cooling-hydrogen savings, the total system weights are not significantly heavier.

Results of Propellant Acquisition Evaluations

- The Attitude Control Propellant Supply presents the most severe requirements for propellant acquisition. The propellant must be provided while accelerations are occurring in any direction and at a relatively high flow-rate.

- The accelerations produced by the ACPS are of sufficient magnitude that retention by a single surface tension screen results in very low pore diameters. Therefore, a multiple screen arrangement appears to be the most satisfactory approach, which results in the allowable stabilized heads of the screens to be additive.

- Some gas ingestion into a propellant acquisition device is considered to be unavoidable.

- The gallery type of acquisition device, which is considered to be the only practical design, results in high start transient pressure losses. Line diameters of up to ten inches may be required for the Gas/Gas ACPS systems.

	Gas/Gas ACPS Subcritical			Gas/Gas ACPS Supercritical Storage	Liquid/Liquid ACPS Maximum Hydrogen Temperature $54^{o}R$					
	Turbopump	Electrical Motor-Driven Pump			Turbine		Motor - 3 Generators		Motor - 4 Generators	
		Three Sets	Four Sets		Bellows 20% Contraction	Bellows 100% Contraction	Bellows 20% Contraction	Bellows 100% Contraction	Bellows 20% Contraction	Bellows 100% Contraction
System Dry Weight lb	3,009	4,168	3,778	5,713	3,580	2,847	4,245	3,512	4,077	3,344
System Wet Weight lb	11,198	11,672	11,392	14,053	11,718	10,985	11,776	11,043	11,608	10,875
Advantages	1. Subcritical Storage provides lower storage weight 2. Gas distribution requires minimal thermal controls	1. Subcritical storage provides lower storage weight 2. Gas distribution requires minimal thermal controls 3. Electrical motor reduces heat soakback and cooling requirements		1. Pump not required 2. Gas distribution requires minimal thermal control	1. Subcritical storage provides low weight 2. Lower performance turbopump		1. Subcritical storage provides low weight 2. Lower performance pump 3. Electric motor results in less heat soakback		1. Subcritical storage provides low weight 2. Lower performance pump 3. Electric motor results in less heat soakback 4. Four generators provide FO/FS for less weight	
Disadvantages:	1. Requires high-performance pump 2. Requires high-performance heat exchanger	1. Requires high-performance pump 2. Requires high-performance heat exchanger 3. Higher weight than turbopump system		1. High tankage weight 2. Moderate high-performance heat exchanger	1. Pumps required 2. Relatively large bellows required 3. Liquid distribution requires more thermal control than gas distribution		1. Pumps required 2. Relatively large bellows required 3. Liquid distribution requires more thermal control than gas distribution		1. Pumps required 2. Relatively large bellows required 3. Liquid distribution requires more thermal control than distribution	

Table 6.4-1
COMPARISON OF ACPS TYPES, STORAGE MODES, AND PUMP DRIVE METHODS

FOLDOUT FRAME 1

FOLDOUT FRAME 2

6.5 AUXILIARY POWER UNIT SUPPLY

The Auxiliary Power Unit (APU) supply tradeoff evaluation involved both the supply concepts and parameters associated with the Auxiliary Power Units. The results present the optimum relationships between supply systems and the APU characteristics. The evaluation encompassed:

- Type of storage

  The types of storage and the associated conditioning system for:

  (a) Subcritical storage

  This system requires pumps for pressurization.

  (b) Supercritical storage

- APU Turbine Inlet Pressure

  The APU turbine inlet pressure has a significant effect upon the supply system, particularly the supercritical storage.

- APU Operating Mixture Ratio

  The mixture ratio (or O/F ratio) of the reactants supplied to the APU affect not only the storage volumes, but also the temperature of the gases supplied to the APU gas generators.

- Approach to Achieving Desired Maximum Horsepower

  The number of APUs utilized in the subsystem to achieve maximum horsepower capability is a function of the redundancy approach. The APUs must be capable of supplying full horsepower requirements after the failure of two units. For example, the 850 hp requirement may be accomplished by:

  (a) Each unit of three units having a capability of 850 hp (allowing two failures)

  (b) Four units each having 425 hp and allowing two failures.

Also, during the operation of the APUs, at least an "extra" unit must be running at all times when the APU is required, resulting in:

(a) For a total of three units, two must be running.

(b) For a total of four units, three must be running.

Since the specific reactant consumption is a function of the percentage of full power, the approach to redundancy has an effect on the system optimization.

The APU requirements result in relationships between specific reactant consumption, mixture ratio, and gas-generator (turbine-inlet) pressure, which result in multiple variable tradeoff considerations.

A summary of comparisons between various approaches is presented in Table 6.5-1. Each of the cases shown has been optimized with regard to gas-generator (turbine-inlet) pressure and storage conditions. The typical duty cycle was used to establish the differences in reactant quantities.

Several significant conclusions resulted from the APU supply evaluations:

- Subcritical storage of the reactants results in significantly lower weights than supercritical storage of the reactants.

- The effects of oxidizer/fuel ratios are relatively small. In subsystems employing supercritical storage, there is a slight advantage for the lower O/F ratios.

- The optimum turbine inlet pressure effects on the reactant supply system indicated:

  (a) Subsystems employing subcritical storage tended to result in the higher turbine inlet pressures. This is principally the result of having a pump in the subcritical subsystem which eliminates sensitivity to the storage pressure.

(b) Subsystems with supercritical storage result in optimum turbine inlet pressures which are a function of mixture ratio:

For O/F of 0.5 – Near 300 psia
For O/F of 0.9 – Near 600 psia

- Since the APU must operate during ascent and during reentry, it imposes severe requirements on liquid acquisition devices. An all-axis liquid acquisition device is needed for starting in orbit. Such devices are difficult to design for accelerations of over 1g, and other methods of supplying the APUs are necessary during the high-g reentry conditions.

	Subcritical Supply System				Supercritical Supply System			
	Mixture Ratio 0.5		Mixture Ratio 0.9		Mixture Ratio 0.5		Mixture Ratio 0.9	
	3-450 HP	2-850 HP	3-450 HP	2-850 HP	3-450 HP	2-850 HP	3-450 HP	2-850 HP
System Dry Weight - lb	818	831	818	825	1,331	1,370	1,562	1,605
System Wet Weight - lb	1,462	1,497	1,565	1,626	2,145	2,253	2,390	2,484
Advantages:	1. Lower mixture ratio has less required flowrate to produce given horsepower (better specific reaction consumption) 2. Subcritical storage produces lower storage weights		1. Reactant specific volume is lower 2. Subcritical storage produces lower storage weight		1. Lower mixture ratio has less required flowrate to produce given horsepower (better specific reaction consumption)		1. Reactant specific volume is lower	
Disadvantages:	1. Pump required 2. Liquid/gas conversion heat exchanger required		1. Pump required 2. Liquid/gas conversion heat exchanger required		1. High storage weights		1. High storage weights	

Table 6.5-1
COMPARISON OF AUXILIARY POWER UNIT SUPPLY SUBSYSTEMS

FOLDOUT FRAME 1

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FOLDOUT FRAME 2

6.6 FUEL CELL SUPPLY

The Fuel Cell Supply Subsystems requirements are not affected significantly by variations in the consuming subsystem. The number of variables to be considered were less than for the other subsystems evaluated. The major tradeoffs in the Fuel Cell Supply Subsystems are related to:

- Storage Conditions

  The storage approaches and the related distribution subsystems were examined for:

  (a) Subcritical Storage (liquid)
  (b) Supercritical Storage

- Fuel Cell Supply Pressure

  The sensitivity of the supply system to the fuel cell supply pressure was examined. It was considered desirable to determine if there was any advantage to low pressure fuel cells.

A comparison of the subsystems is presented in Table 6.6-1. The subsystems presented were optimized with regard to storage conditions.

<u>Conclusions From Evaluations</u>

The conclusions which were derived from the evaluations are:

- The subcritical and supercritical storage modes result in approximately the same weight subsystems. It was observed that the difference between subcritical storage and supercritical storage decreases as the quantity of propellants and reactants decreases.

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- Considering all factors, supercritical storage would be preferred in individual subsystems.

- There were no advantages to employment of a low-pressure fuel cell.

Table 6.6-1

COMPARISON OF FUEL CELL SUPPLY SUBSYSTEMS

	Supercritical			Subcritical	
	Minimum Supply Pressure			Minimum Supply Pressure	
	20 psia	100 psia	200 psia	20 psia	> 60 psia
System Dry Weight, lb	494	480	484	440	460
System Net Weight, lb	2,202	2,127	2,153	2,165	2,126
Advantages:	1. Storage less critical from the standpoint of thermal insulation and heat leaks			1. Subcritical systems provide low storage weight	
Disadvantages:	1. High storage weights			1. High component weights 2. Storage conditions more severe from the standpoint of thermal protection	

6.7 LIFE SUPPORT SUPPLY

The Life Support Supply subsystem evaluations were principally tradeoffs between subcritical and supercritical storage. High-pressure gas storage, which could be considered as part of the emergency supply system, was not evaluated.

The comparison of the Life Support Supply approaches is presented in Table 6.7-1. The subcritical supply system presented here is not designed to provide the high-pressure (800 psia) required for PLSS recharge. As may be seen from the table, even without this requirement, supercritical storage shows a weight advantage over subcritical storage.

Table 6.7-1

COMPARISONS OF LIFE SUPPORT SUPPLY SUBSYSTEMS

	Supercritical	Subcritical
System Dry Weight (lb)	191	225
System Wet Weight (lb)	313	347
Advantages:	1. No/liquid gas conversion required 2. Thermal effects associated with storage less severe	1. Savings in volume 1. Savings in volume
Disadvantages:	1. More volume	1. Liquid/gas conversion required 2. More thermal problems associated with storage

6.8 PURGING, INERTING, AND PNEUMATIC SUPPLY

The Purging, Inerting, and Pneumatic Supply system definitions were highly dependent upon requirements defined by the subsystem requirements and criteria. Therefore, several subsystem approaches are displayed in the evaluations in order to provide comparative data.

Helium Supply Subsystems

The helium supply subsystem concepts are presented in Table 6.8-1, for a variety of conditions. Reentry with LH_2 in the Orbit Maneuvering propellant tanks assumes that the helium must be employed for insulation purging.

The results of the helium supply subsystems indicated:

- Storage of helium at LH_2 temperature provides the lightest weight system for each of the cases.

- The High Pressure engine as defined by the Interface Control Document requires high flowrates of helium. An interesting result associated with ambient helium storage is that the highflow rates result in large decreases in the helium temperatures requiring heating to meet the engine specifications. The required reactants to provide conditioning are of comparable weight to that required to condition helium stored at the LH_2 temperatures.

- Storage in titanium tankage results in significantly less weight than storage in aluminum tankage.

Nitrogen Supply Subsystems

Various alternatives for the nitrogen supply subsystem are presented in Table 6.8-2. The alternatives presented represent a wide range of nitrogen requirements. The results indicated:

- In general, subcritical storage provides the lowest weight subsystems. However, for the smaller quantities, supercritical storage is almost the same weight, and ambient storage is also competitive.

- The purging of potential nitrogen leakage areas during ascent and reentry to assure hydrogen concentrations below the flammable limits can represent a significant system weight increase. Tank inerting further increases the system weight penalty.

Nitrogen ground purging is necessary for safe operation. The nitrogen is supplied from a main feedline entering the aft region of the vehicles with smaller distribution lines. In evaluation of the nitrogen supply system for ground purging, it was found that a 100-ft feedline could be operated at 100 psia. The line sizes would be:

- 10 lb/sec flow - 3.5 in.

- 20 lb/sec flow - 4.75 in.

Single lines were found to weigh less than multiple lines.

	(1) With LH_2 in OMPS Tank During Reentry (2) With Recirculation of Purge Bag He		(1) With LH_2 in OMPS Tank During Reentry (2) No Recirculation of Purge Bag He		(1) W/O LH_2 in OMPS Tank During Reentry or Vacuum Jacketed	
	Storage at LH_2 Temperature	Ambient Storage	Storage at LH_2 Temperature	Ambient Storage	Storage at LH_2 Temperature	Ambient Storage
System Dry Weight (lb)	712(2) (1,322)(1)	1,468	607(2) (1,147)(1)	1,393	596(2) (1,147)(1)	1,373
System Wet Weight (lb)	1,179(2) (1,789)(1)	1,580(1) or 1,835(2)	828(2) (1,368)(1)	1,490(1) or 1,518(2)	812(2) (1,343)(1)	1,367(1) or 1,495(2)
Comments:	(1) Number in parenthesis represents aluminum tankage (2) Number without parenthesis represents titanium tankage	(1) Lower number considers all heat addition from environment (2) Higher number considers all heat addition supplied by O_2/H_2 heat exchanger for high-flowrate withdrawal	(1) Number in parenthesis represents aluminum tankage (2) Number without parenthesis represents titanium tankage	(1) Lower number considers all heat addition from environment (2) Higher number considers all heat addition supplied by O_2/H_2 heat exchanger for high withdrawal rate	(1) Number in parenthesis represents aluminum tankage (2) Number without parenthesis represents titanium tankage	(1) Lower number considers all heat addition from environment (2) Higher number considers all heat addition supplied by O_2/H_2 heat exchanger for high-flowrate withdrawal
Advantages:	1. Lower storage weight 2. Lower storage volume	1. Conditioning not required except at high flowrates	1. Lower storage weight 2. Lower storage volume	1. Conditioning not required except at high flowrates	1. Lower storage weight 2. Lower storage volume	1. Conditioning not required
Disadvantages:	1. Conditioning always required	1. Higher storage weight	1. Conditioning always required	1. Higher storage weight	1. Conditioning always required	1. Higher storage weight

Table 6.8-1
COMPARISON OF HELIUM SUBSYSTEM ALTERNATIVES FOR PURGING, INERTING, AND PNEUMATIC SUPPLY

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	(1) Vacuum-Jacketed OMPS Tanks (2) W/O H_2 Leakage Purging			(1) W/O H_2 Tank Inerting (2) W/O H_2 Leakage Purging			(1) W/O H_2 Tank Inerting (2) With H_2 Leakage Purging			(1) With H_2 Tank Inerting (2) With H_2 Leakage Purging			(1) W/O H_2 Tank Inerting (2) W/O OIPS Leakage Purging		
	Sub-Critical	Super-Critical	Ambient Storage	Sub-Critical	Super-Critical	Ambient Storage	Sub-Critical	Super-Critical	Ambient Storage	Sub-Critical	Super-Critical	Ambient Storage	Sub-Critical	Super-Critical	Ambient Storage
System Dry Weight (lb)	92	141	133	172	187	185	238	453	2,479	314	682	4,334	218	221	319
System Wet Weight (lb)	103	152	144	189	204	202	1,726	2,033	3,958	2,977	3,507	6,978	323	332	423

	Subcritical	Supercritical	Ambient Storage
Advantages:	1. Lighest weight in all cases	1. Comparable to subcritical for smaller N_2 requirements	1. Comparable to other storage methods for small quantities 2. Requires no conditioning for lower flowrates
Disadvantages:	1. Requires conditioning 2. Propellant acquisition for large flowrates	1. Requires conditioning	1. Heavier subsystem for larger quantities 2. Larger volume required

Table 6.8-2
COMPARISON OF NITROGEN SUBSYSTEM ALTERNATIVES FOR PURGING, INERTING, AND PNEUMATIC SUPPLY

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Section 7

RESULTS OF INTEGRATED SYSTEMS TRADEOFF STUDIES

The Integrated Systems tradeoff studies have initially examined the integration of optimum subsystem approaches. Subsystems were modified as necessary to provide the most desirable approaches to integrated systems. The information provided in this section attempts to provide an overview of the results presented in Section 10.

7.1 GENERAL APPROACH

The task of integrating these systems was very complex in that several hundred combinations of integrations are available. The overall approach and the potential areas of integration are described in Section 10. Storage of the cryogens was selected as the primary mode of integration. Other integration modes - such as types of pumps, feed systems, pressurization, and thermal control - were considered as supplements to the storage method. Eight major groups of subsystem integration were identified as being representative of the various degrees of integration. Perturbations of these groups to reflect some specific design approaches resulted in 16 cases. Analysis of these cases resulted in a weight statement, component count, and operational characteristics for each.

7.2 CANDIDATE SYSTEMS

Descriptions of the systems are summarized in Table 7.2-1, and the weights, component counts, and statements of advantages and disadvantages are listed in Table 7.2-2. Selection of eight major groups was based upon the degree of common storage and on utilization of subcritical or supercritical tankage. The first groups, Integrated Systems I, have all the cryogens, except for the OIPS, stored in common subcritical tanks. In each succeeding system or group, less commonality of tankage is employed and various degrees of subcritical and supercritical storage are employed. This is indicated by the boxes listed under each integrated system number and opposite the heading of "Subcritical" or "Supercritical".

C

7.3 SUMMARY DESCRIPTIONS OF CANDIDATE SYSTEMS

7.3.1 Storage Considerations

The cryogen storage considerations are as follows:

- Cases Ia, b, and c - all cryogens stored in common subcritical tankage
- Cases IIa and b - OMPS, ACPS, and APU stored in common subcritical tankage; FC and EC/LSS cryogens stored in common supercritical tanks
- Cases IIIa and b - OMPS and ACPS cryogens stored in common subcritical tankage; IIIa APU cryogens stored in separate subcritical tank; FC and EC/LSS cryogens stored in common supercritical tankage; IIIb APU cryogens stored in separate supercritical tanks.
- Remainder of systems follow a similar pattern

Propellants for the OIPS system are in no way integrated with the other systems. The primary mode of integration of the OIPS is either (1) by using the tanks and residuals as a heat sink for on-board heat generation, or (2) by having the prepressurant supplied from the ACPS gas accumulators. The weights listed in Table 7.2-2 include 3,298 lb of inert weight for the OIPS system. This includes lines, valves, and pressurization system only; these are based on the assumption that the prepressurant is supplied from the ACPS gas accumulator. Studies described in Section 10 show that the ascent tanks can be used as a heat sink during the early part of the mission; however, the weights and component counts required to implement two types of cooling are not included. The number of components listed for each system does not include the OIPS components.

7.3.2 Vacuum Jackets and Acquisition Systems Considerations

The systems are described as to whether or not vacuum jackets are employed on the storage tanks and what type of acquisition system is used.

INTEGRATED SYSTEM	Ia	Ib	Ic	IIa	IIb	IIIa	IIIb	IVa	IVb	IVc	Va	Vb	VIa	VIb	VII	VIII
STORAGE																
SUBCRITICAL	OMPS ACPS APU FC EC/LSS	OMPS ACPS APU FC EC/LSS	OMPS ACPS APU FC EC/LSS	OMPS ACPS APU	OMPS ACPS APU	OMP ACPS APU	OMPS ACPS	OMPS ACPS	OMPS ACPS	OMPS ACPS	OMPS ACPS APU FC EC/LSS	OMPS ACPS APU FC EC/LSS	OMPS	OMPS	OMPS ACPS APU	OMPS
VACUUM JACKET	YES	YES	NO	YES	NO	NO YES	NO	NO	NO	YES	NO YES	SAME	NO	NO	NO YES	NO
ACQUISITION	COMPARTMENT WITH HEADS	COMPARTMENT WITH HEADS	START TANK + CHANNELS + HEADS	COMPARTMENT WITH HEADS	START TANK WITH HEADS	COMPARTMENT WITH HEADS CHANNELS AND HEADS	COMPARTMENT WITH HEADS	COMPARTMENT WITH HEADS	START TANK WITH HEADS	COMPARTMENT WITH HEAD	START CONTAINER CHANNELS AND HEADS	SAME	START CONTAINER	COMPART-MENTED WITH HEADS	START CONTAINER CHANNELS AND HEADS	START CONTAINER
SUPERCRITICAL(1)(2)(3)				FC EC/LSS	FC EC/LSS	FC EC/LSS	APU FC EC/LSS	APU FC EC/LSS	APU FC EC/LSS	APU FC EC/LSS			ACPS APU FC EC/LSS	ACPS APU FC EC/LSS RESUPPLIED FROM OMPS	FC EC/LSS	ACPS APU FC EC/LSS
PUMP	COMMON AT TANK FOR LIQUID TO OMPS AND TO ACPS HEAT EXCHANGER	COMMON AT TANK FOR LIQUID TO ACPS HEAT EXCHANGER RL-10 ENGINES FOR OMPS	SAME	COMMON AT TANK FOR LIQUID TO OMPS AND TO ACPS HEAT EXCHANGER	SAME	COMMON AT TANK FOR LIQUID TO OMPS AND TO ACPS HEAT EXCHANGER SEPARATE FOR APU	SAME	COMMON AT TANK FOR LIQUID TO OMPS DUE TO ACPS HEAT EXCHANGER	SAME	SAME	RL-10 FOR OMPS, COMMON AT TANK FOR ACPS	SAME	RL-10 FOR OMPS	RL-10 FOR OMPS + REFILL PUMP AT OMPS TANKS	RL-10 FOR OMPS AT TANK FOR ACPS AND APU	RL-10 FOR OMPS
PRESSURIZATION(4)	He	He	He IN START TANK; GH_2 IN LARGE TANK	He	He IN START TANK; GH_2 IN LARGE TANK	He	He	He	He IN START TANK; GH_2 IN LARGE TANK	He	FOR OMPS GO_2, AND GH_2 SUPPLIED FROM ACPS; He IN ACPS He	He	FOR OMPS GO_2 AND GH_2 SUPPLIED FROM ACPS	He FOR OMPS	He He	FOR OMPS GO_2/GH_2 SUPPLIED FROM SUPERCRITICAL ACPS

(1) ALL SUPERCRITICAL STORAGE VESSELS EMPLOY VACUUM JACKETS.
(2) NO PUMPS USED WITH SUPERCRITICAL STORAGE TANK.
(3) NO ACQUISITION USED WITH SUPERCRITICAL STORAGE TANKS.
(4) INDICATED PRESSURANT IS FOR SUBCRITICAL TANKS ONLY.

Table 7.2-1
INTEGRATED SYSTEMS DESCRIPTION SUMMARY

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These two headings apply only to the subcritical storage tanks, because (1) vacuum jackets were always employed on the supercritical tankage for these cases and (2) no acquisition device is needed for supercritical fluids.

When two sets of subcritical tanks are indicated for different arrangements of subsystem cryogens, the indication of whether or not they are vacuum jacketed is described by listing two statements, one above the other. The upper one pertains to the first listed tank and the lower one to the second listed tank. For example in Case IIIa, the subcritical OMPS and ACPS cryogen tanks do not have vacuum jackets and the subcritical APU cryogen tanks do have vacuum jackets.

There are four types of acquisition devices employed for the listed cases. One device is listed as "compartment with heads". This system employs a membrane in the large tanks that tends to compartmentalize the volume into smaller sizes that are more amenable to the fluid surface tension, density, and imposed acceleration. The membrane contains screen-covered holes so that fluid may transfer from the larger portion of the tank to the compartment. Negligible pressure differences are obtained between the two regions. Within the compartment, a series of channels and screened acquisition heads are arranged to supply fluid to the feed system against the adverse acceleration.

Another acquisition system is called "start tank + channels + heads". This system is similar to the above described system, except that the compartment consists of a vessel within the main tank; the vessel is capable of withstanding several psi differential pressure and can be refilled during OMPS engine operation.

A third device, identified as "channels + heads", is employed when the tanks are relatively small. The same principles of utilizing channels and screened acquisition heads as discussed above are used, but compartments or pressure vessels are not required, because the tanks are relatively small.

The fourth device called a "start container" is an acquisition device placed in the OMPS tanks only. It is a relatively small hat-shaped screened container that is used only for OMPS engine starts. It is not required to continually supply feed systems against an adverse acceleration.

7.3.3 Pump Arrangements

Two basic pump arrangements have been utilized for the various integrated systems. One arrangement is to use the RL-10 engine to supply the OMPS propellant and a new turbopump set to supply the other subcritical systems. The other arrangement is to utilize a single type of turbopump set to supply all subsystems, including the OMPS. When a newly designed turbopump set is employed, it is placed near the tank to minimize tank pressure. This has been referred to as "pump-at-the-tank" in the various tradeoff studies. When the RL-10 is employed, it is referred to as "pump-at-the-engine". For the various cases, there are combinations of these two arrangements that include (1) using a turbopump set located near the tank to supply all cryogens, (2) using an RL-10 to supply OMPS propellants and a turbopump set for other subsystems, and (3) using only an RL-10 for the OMPS and no turbopump set for the supercritical systems. In case Ia, the turbopump set supplies liquid to the OMPS thrusters and alternately to a heat exchanger for conditioning and storage in a high-pressure accumulator. The other subsystems use gas from the accumulators. Case IIIa employs a similar arrangement but utilizes a separate pump for the APU, which is designed for that specific purpose.

7.3.4 Pressurization

The pressurization heading, shown in Table 7.2-1, applies only to the subcritical tanks. Two types of systems were considered here. Either the prepressurant and pressurant is helium or it is warm GO_2 or GH_2. Generally, anytime it was necessary to prepressurize, flow the cryogen, and maintain pressure helium was employed. In those cases where the OMPS is separate, GO_2 and GH_2 pressurant was investigated.

7.4 ATTRACTIVE POTENTIAL BASELINE SYSTEMS

The results of the various analyses are shown in Table 7.2-2. Inert weights and wet weights are noted for each system, and the various advantages and disadvantages are listed. Systems I and III have been tentatively identified as good baseline systems.

7.4.1 System Ia Discussion

7.4.1.1 Advantages of System Ia. This system is relatively light, has few components, and provides straightforward operational characteristics. The use of common subcritical storage tanks provides a lightweight approach that has inherent versatility, inasmuch as cryogens may be divided in any fashion even after the mission has been initiated. These tanks are vacuum-jacketed, which helps the operational situation in that no helium purge around the tank is required on the ground and during reentry. The insulation is well protected. Heat rates to the tank are always controlled - thus, permitting the tanks to be in an operational state throughout the entire mission. Vacuum jackets permit the possibility of no venting during reentry and subsequently the potential of helium reclamation from the tank during refill. The use of common turbopump sets for supplying both the accumulators and the OMPS thruster provides a minimum number of development items. The location near the tank along with a low NPSP permits low-tank pressures and net weight savings. Newly developed thrusters permit a high specific impulse. The helium pressurant provides a lightweight pressurization system and permits maintenance of the propellant in a subcooled state. The reusability and reliability analysis shows that the systems employing a turbopump set located at the tank tend to yield a lower probability of failure than the system with pumps at the engine, primarily because of the added number of chilldown components associated with the pump at the engine.

7.4.1.2 Disadvantages of System Ia. System Ia has some disadvantages. New development is required on the turbopump and OMPS thrusters. A turbopump must be developed regardless of what system is selected. A potential problem area is associated with the acquisition system for the arrangement of System Ia. The combination of size, fluids, and mission profile creats a difficult set of design requirements. The large tanks that are required to hold all of the propellant, including that required for a Δ V reserve of 500 ft/sec, cause large dimensions against which surface-tension devices must support a column of liquid. The combination of low fluid surface tension and/or relatively high densities causes small or multiple screens to be used to yield effective capillary forces. To aid this problem, the tanks must be divided into compartments so that smaller effective dimensions can be achieved; this adds weight to the system, but the weight is not excessive. The requirements of System Ia to withdraw fluid from the tank while on the ground in a vertical launch position, throughout ascent, during orbital flight, through reentry, during atmospheric flight, and finally during landing impose a variety of design conditions that must be handled by a single device. This can be accomplished by utilizing covers that act as slosh baffles during the level atmospheric flight and during withdrawal of fluid for the APU and FC. Although approaches have been developed so that there is confidence that such a system can be developed, it is worthwhile to identify the acquisition system as a potential problem area.

7.4.2 System IIIa Discussion

7.4.2.1 Advantages to System IIIa. System IIIa is attractive, because it is relatively light and embodies some desirable features that system Ia lacks. The most significant feature is the separation of the APU and FC and EC/LSS from the common OMPS and ACPS storage tanks. Those cryogens that are required to be used in the atmosphere as well as on-orbit are placed in their own vacuum-jacketed tanks. The OMPS and the ACPS propellants are commonly stored in a nonvacuum-jacketed tank. This requires that the multilayer insulation be helium-purged during launch and reentry. However, because the last propellant-flow requirement from the OMPS-ACPS tanks occurs early in the reentry phase, the tanks can be vented.

APU reactants are stored separately in their own subcritical vacuum-jacketed tanks, and each reactant is supplied to the APU with its own pump. The APU system is entirely separate from the other systems.

FC and EC/LSS cryogens are stored in common supercritical vacuum-jacketed tanks. The relatively high-bulk density of the FC reactants makes possible the use of supercritical tanks at a minimum weight penalty. The relatively low flowrate from these tanks allows for easy heat transfer (1) to the tanks for maintaining pressure and (2) to the fluid for conditioning prior to its supply to the fuel cell module. The environmental control system can easily supply this heat, and Freon-21 cryogenic heat exchangers can be designed and controlled, if the Freon flowrate is not permitted to drop.

A common pump at the tank is utilized to supply both the ACPS accumulators and liquid to the OMPS thrusters. This arrangement is the same as for System Ia.

The division of the cryogens into separate tankage and separate subsystems reduces the design requirements placed on any particular component or element, in that it must be designed only for the particular requirements and mission parameters peculiar to the specific subsystem. This is especially true for the propellant acquisition system. Design requirements for the propellant acquisition devices for System IIIa are somewhat reduced from those for System Ia, inasmuch as each acquisition system need only function under limited conditions. The acquisition devices in the OMPS-ACPS tanks are very similar to those in System Ia in that the tanks are large and compartmenting is still required. However, the acquisition devices need to operate only during the relatively low adverse acceleration environments while on-orbit and during the early phases of reentry.

Acquisition devices in the APU must operate during low gravity (orbital start of the APU) as well as during one g. However, during the launch phase of one-g flight, the tanks never drain more than 1/3 of their capacity, and drains can be provided near the side and aft portion of the tank and still function. This drain position then is ideal for the near horizontal portion of atmospheric flight when the tanks are nearly empty. Since the tanks are nearly full during low-gravity orbital start, only one or two communication channels need be provided near the midpoint of the tank to assure supply during the low-gravity deorbit period. The tanks are relatively small and tank compartmenting is not required.

The supercritically stored FC and EC/LSS cryogens do not require an acquisition device.

7.4.2.2 Disadvantages to System IIIa. The drawbacks of System IIIa lie primarily in the following areas:

- Reduced versatility of using the cryogens in alternate fashions
- Reduced operational flexibility and insulation protection by not having a vacuum jacket on the OMPS-ACPS tanks
- Additional development required by the larger number of different components

The first of these drawbacks may not be too severe, because the greatest potential requirement for flexibility lies in the utilization of orbit maneuver propellant versus attitude control propellant. Since the propellants for these two functions are stored in common tanks, a great portion of the flexibility is retained.

The second drawback can be overcome by the utilization of a vacuum jacket. However, the system dry weight would increase.

There is no way around the third drawback, except that development of separate complete subsystems - such as the APU and FC - might be slightly easier than more sophisticated integrated systems.

The greater number of components required by System IIIa does not seem to create a significant change in overall system reliability on component replacements as compared to System Ia.

7.5 COMPARISON OF THE REUSABILITY AND RELIABILITY OF SYSTEM I AND SYSTEM III

Reusability and reliability analyses are presented in Section 11 of this report. In these evaluations, comparisons were made of System I and System III Integrated Systems. The comparisons presented in Fig. 7.5-1 are for the pumps located-at-the-engines but are considered representative of results for the pump-at-the-tank. These results indicate that both systems have very comparable probabilities of failure over a given number of missions, and similar component replacement, even though the storage conditions vary considerably. This is because those components eliminated by going from System III to System I were ones with low-duty cycles and good lifetimes, which did not significantly shift the reusability and reliability considerations.

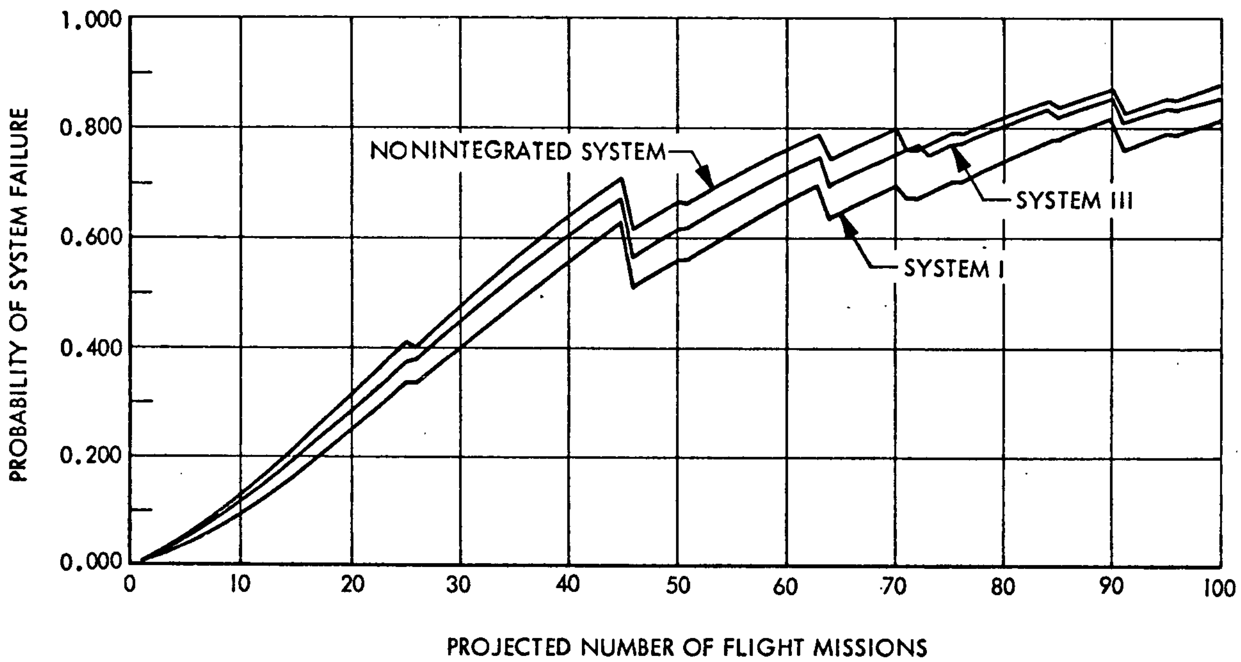

Fig. 7.5-1 Comparison of Relative Reliability of System I, System III, and Nonintegrated Systems (Pump-at-Engine)

Section 8

RESULTS OF COMPONENT STUDIES

Component evaluations were given considerable emphasis in the study. AiResearch was employed as a subcontractor to provide depth to the evaluations. Lockheed and AiResearch examined each of the potential components in the subsystems. The subsystem sensitivity and tradeoff studies contributed significantly to the component data. The steps in the evaluation were:

- Component data compilation
- Reusability and reliability evaluations
- Component evaluations

The large amount of component data compiled has been presented in the Task Reports. A summary of the available Task Reports is presented in Section 12 - References.

8.1 COMPONENT DATA COLLECTION

Lockheed prepared reference subsystems which represented each of the shuttle applications. These were examined by Lockheed and AiResearch and components were specified to satisfy the applications.

Parametric data were generated for:

- Valves and regulators
- Heat exchangers
- Pumps
- Tankage
- Tank vacuum shells
- Feedlines
- Feedline components
- Fluid acquisition devices

- Multilayer insulation
- Groundhold and ascent insulation (foams and batting)

Additional data were generated and collected for:

- Electrical motors
- Thermal conditioning units (including control approaches)
- Instrumentation components

Leakage analyses were performed to determine the importance of component leakage. The analyses examined propellant and helium losses and over-pressurization as a function of leakage rates.

The results of the component data collection indicated:

- For most of the valving, components satisfying the requirements were found to be existing.

- Heat exchanger designs were found to be within the state-of-the-art.

- Pump designs were defined, but technology developments are required.

- Fluid acquisition device parametric data indicated that technology development is required.

- Satisfactory instrumentation components are lacking for certain applications.

8.2 REUSABILITY AND RELIABILITY EVALUATIONS

Reusability and Reliability were recognized as being closely related and were evaluated in the same task. An effort was made in the study to increase the quantitative assessment of Reusability and to show its relationship to Reliability. Reliability was presented in terms of providing comparisons between various approaches. The combining of "Reusability" and "Reliability" into a single concept term "Predictability", as applied to shuttle concepts, was explained and recommended.

Data were collected for the evaluations from a number of sources by both Lockheed and AiResearch. The data included:

- Lifetime estimates
- Most likely malfunction
- Failure rate estimates

Reference subsystems were established and initial redundancy evaluations were performed using a computer program (SETA II) to determine the "weakest" components in the subsystems by their effect on Reliability. Failure mode and effect analyses were also conducted.

Predictability evaluations were performed utilizing the principle integrated systems and individual subsystems resulting from the concept studies.

These predictability evaluations compared integrated system approaches and nonintegrated systems while, at the same time, evaluating the lifetime of components in their respective duty-cycle applications. Different approaches to utilizing redundancy were examined in these studies.

There are two probabilities of failure for consideration in reusable systems:

- The probability of failure per flight (or probability of unscheduled maintenance), which is a constant for all flights, if constant failure rates for the components may be assumed. This is essentially a function of the effective redundancies in the subsystems, and of course, the failure rates of the components.

- The probability of failure in "N" number of flights, which does not relate to the probability of failure per flight but is an excellent indicator for the comparison of reusable subsystems. This is affected by the lifetime of the components within the subsystems.

Results of comparisons of different operational modes and different degrees of integration are summarized in Figure 8.2-1. It may be seen that the degree of integration had only a small effect on the probability of unscheduled maintenance over a given number of flights. The effect of integration was greater on the "per mission" results shown in parenthesis by each system.

The modes of operation referenced in Figure 8.2-1, are designated "preselected operation" and "sequential operation". "Preselected operation" assumes that where parallel redundancy exists (FO/FS), a single path would be selected for operation with only minimal operation of the alternate paths. "Sequential operation" refers to distribution of the load between the parallel paths in a relatively equal manner. The results indicate that "preselected operation" shows a significant improvement over "sequential operation" in unscheduled maintenance, both per flight and over a given number of missions.

An important conclusion resulting from the predictability evaluations was that component duty cycles for the shuttle cyrogenic supply systems are not severe from the standpoint of component wearout. Material lifetimes from the standpoint of environmental exposure are likely the most important factors influencing maintenance. Degradation of organic materials was identified as the most severe lifetime constraint. The malfunction of bellows and diaphragms in cryogenic components was identified as a significant failure mode.

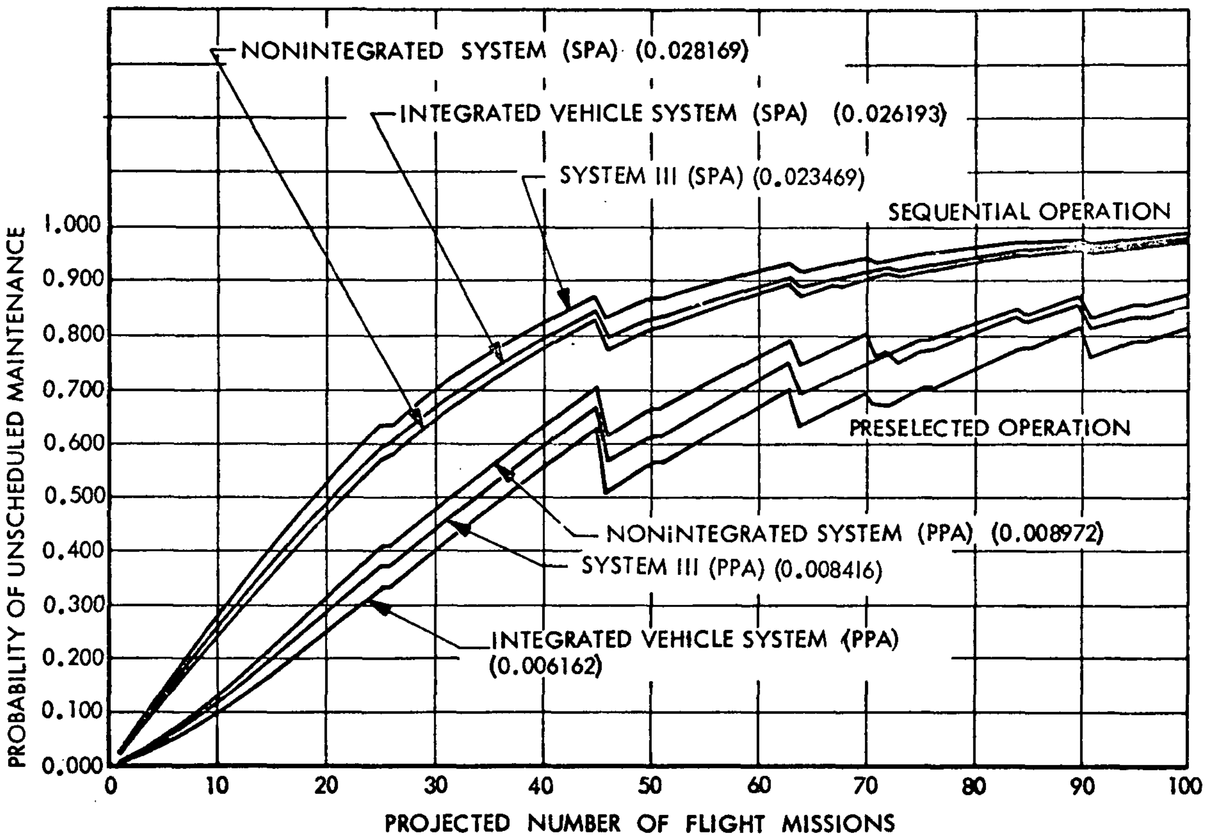

Fig. 8.2-1 Effect of Operational Mode as Compared to Integration Method

8.3 TECHNOLOGY EVALUATIONS

The identification of needs for technology improvements and advancements was considered a major program objective. Technology assessments were made during all phases of the contract. The detailed analyses were utilized to determine the sensitivity of the subsystems to technology status, such as insulation effectiveness. AiResearch assisted in these evaluations by examining component technology requirements. In the examinations, the identified technology items were classified as:

- Basic data requirements
- Improvements in analytical techniques
- Mechanical and electrical components
- Instrumentation and control
- Tankage
- Feedlines and feedline components
- Propellant acquisition
- Insulation
- Subsystem technology development

A significant conclusion resulting from the study was that the majority of the identified improvements considered to be necessary or desirable for the supply system components can be classified as design improvements rather than technology advancements. The major technology advancements and/or design improvements identified are summarized in Table 8.3-1.

The technology requirements considered to be the most significant are:

- Propellant Acquisition

Propellant acquisition is considered to be the major requirement for technology advancement. The propellant-acquisition devices must be developed for the required vehicle accelerations and must have the necessary thermal integrity. These propellant acquisition devices will be subject to gas injection from being stressed without being in contact with liquid. During the start transient, the pressure drop from accelerating liquid will provide a different source of stress on the acquisition device. The bubble pressure of the screen must resist pull-through during the acceleration of flow.

- Cryogenic Pumps

The cryogenic pumps are identified as the second significant technical problem. The pumps were not listed as the primary problem, since alternatives exist that can relax the requirements for rapid start transients.

- Groundhold, Ascent, and Reentry Insulation

Insulations, such as foam or gas barrier that must perform in the atmosphere, are considered to be major thermal protection problems. The principal problems here are related to physical problems and reusability.

- Pressurization Analytical Techniques

Pressurization and related stratification evaluations present the major problems in analytical techniques. The potential benefits from optimizing pressurization are equal to significant gains in thermal protection effectiveness.

Basic Data	Improvements In Analytical Techniques	Mechanic and Electrical Components	Instrumentation and Control	Tankage	Feedline and Feedline Components	Propellant Acquisiton	Insulation	Subsystem Technology
(1) Extension of data on solubility of helium in cryogenics (2) Hydrogen flame data (3) Fracture mechanics data (4) Organic material lifetime data for shuttle mission profiles (5) Cryogenic-fluid capillary-retention properties (6) General bellows data	(1) Improvements in pressurization analytical techniques (2) Improvements in cryogenic-fluid stratification analyses (3) Analysis of insulation purging	(1) Cryogenic pumps for ACPS (2) Cryogenic pumps for APU (3) Cryogenic-cooled electrical motors (4) Cryogenic disconnect improvement (5) FO/FS actuator designs	(1) Pressure switch lifetime improvement (2) Liquid-hydrogen pressure-transducer development (3) Leakage-detection devices (4) Temperature-controlled venting	(1) Composite material development and lifetime evaluation (2) Vacuum shell improvement	(1) Aluminum feedline development (2) Vacuum sealoff valve improvement	(1) Device Development	(1) Groundhold, ascent, and reentry insulation (2) Feedline insulation (3) Breathing insulation system testing	(1) Liquid/liquid attitude control (2) Electrical integration of the cryogenic subsystems (3) Subsystem integrated control (4) Cryogenic cooling

Table 8.3-1 LISTING OF IDENTIFIED TECHNOLOGY AND IMPROVEMENT

Section 9

SUBSYSTEM SENSITIVITY AND TRADEOFF ANALYSES

As previously noted, the subsystem sensitivity and tradeoff analyses were performed with consideration that the subsystems would principally function as individual subsystems and not as part of the integrated systems. The subsystem tradeoff analyses are provided in this section of the Interim Report in sufficient depth to:

- Provide an understanding of the detailed approach
- Explain the analytical methods that were employed
- Present the results of sensitivity studies
- Display the detailed tradeoff studies to a greater depth than presented in the previously presented results.

9.1 ORBIT MANEUVERING PROPELLANT SUPPLY (OMPS)

The Orbit Maneuvering Propellant Supply (OMPS) subsystem, which involved more analyses and evaluations than the other subsystems, is the principal key to the possible integration of the orbiter subsystems. The overall approach employed in the OMPS sensitivity and tradeoff analyses is presented in Fig. 9.1-1.

9.1.1. Selection of Candidate Subsystems

Major differences between the OMPS subsystem arrangements are established by:

- Vehicle configuration constraints
  - Single tanks
  - Dual tanks (cascaded or noncascaded)
- Location of pumps
  - Pumps at-the-engines
  - Pump at-the-tank
- Start Tanks

These differences in overall approach are shown in Fig. 9.1-2. Spacecraft layouts were presented in Section 4. Important characteristics associated with the engines and pumps for the pump at-the-engine and the pump at-the-tank were presented in Section 5. The possible general perturbations of the component arrangements within the OMPS are presented in Fig. 9.1-3.

9.1.1.1 Schematics for Component Evaluations at AiResearch. Orbit Maneuvering Propellant Supply schematics systems were prepared and submitted to AiResearch for the selection of components. These schematics, presented in Appendix E, were formulated to represent the possible component arrangements presented in Fig. 9.1-3. Also, the schematics were used to perform the initial redundancy analyses using the SETA II computer program. The identified redundancies (presented in Appendix E) established the least-reliable components in the subsystems.

9.1.1.2 Schematics for Sensitivity and Tradeoff Studies. Detailed schematics were prepared for the OMPS concepts for use in the tradeoff and evaluation studies. These schematics were put through several iterations, which principally were the result of examinations regarding compliance with safety criteria and with instrumentation and control.

In addition to those major items previously listed that differentiate the systems, several others are noted that provide similarities or differences:

- Retention of propellants in lines or dumping propellant

  If the propellants are not retained in the feedlines, it is necessary to provide a chilldown capability

  If the propellants are retained in the lines, it is necessary to provide a hydrogen-cooling system.

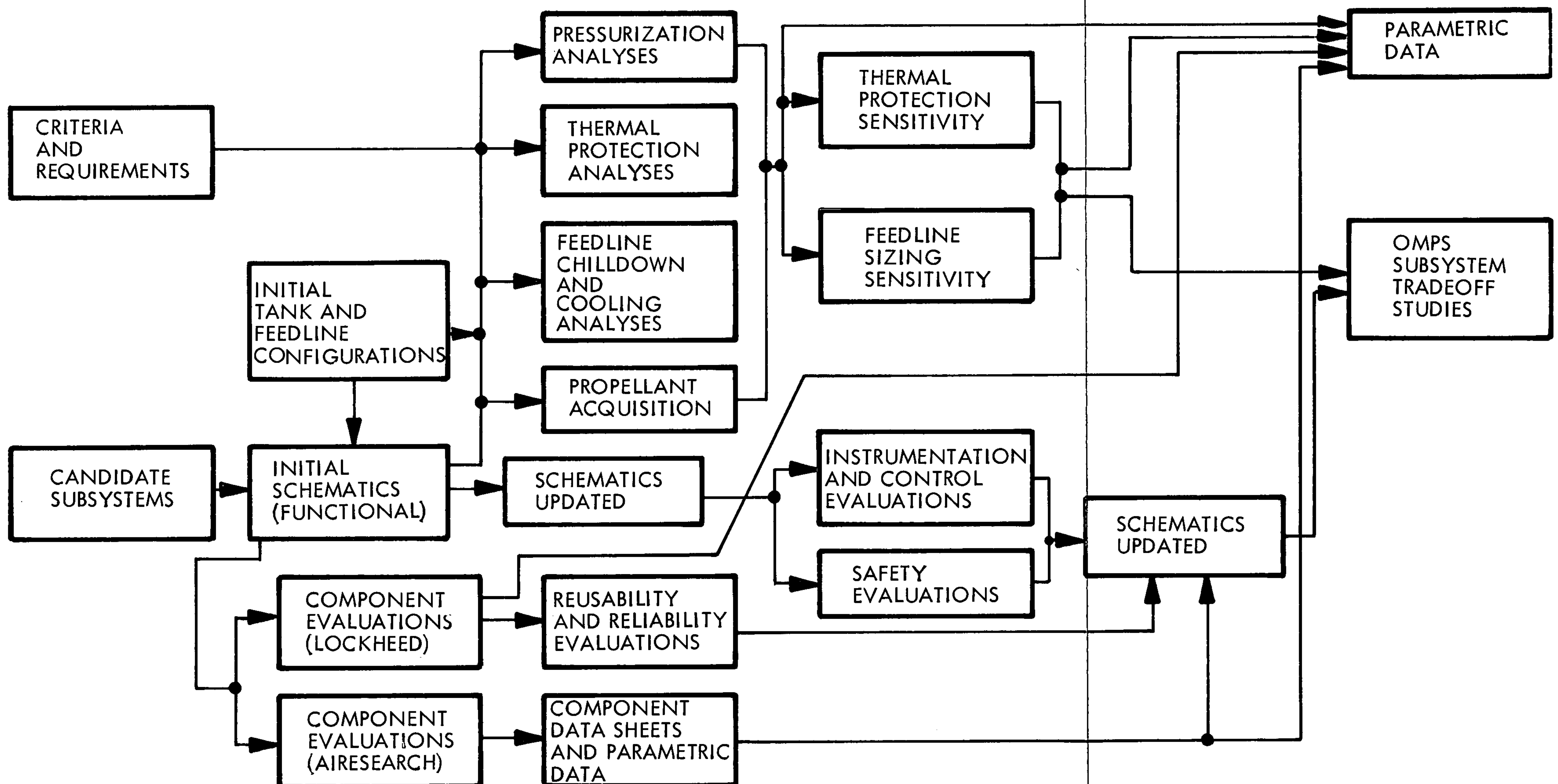

Fig. 9.1-1 Approach to Orbit Maneuvering Propellant Supply Evaluations

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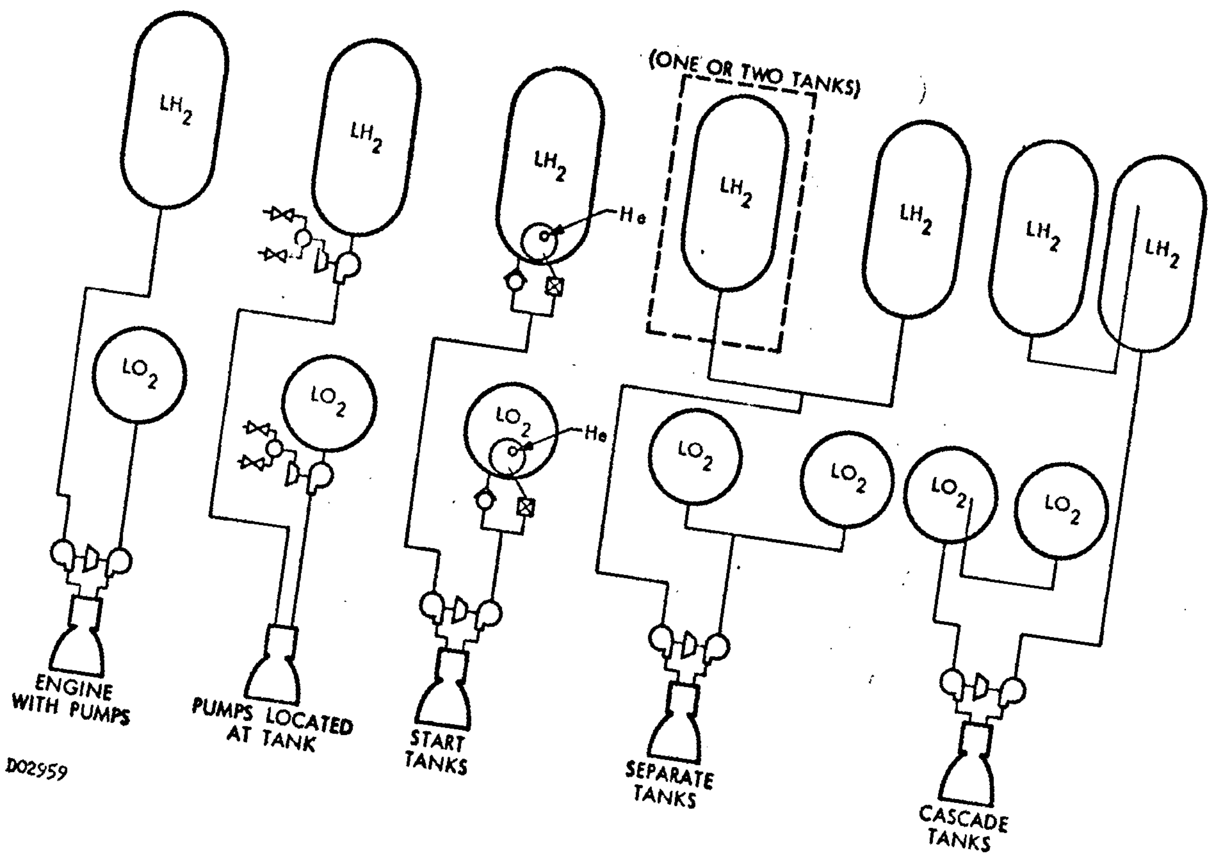

Fig. 9.1-2 OMPS Feed System Configuration

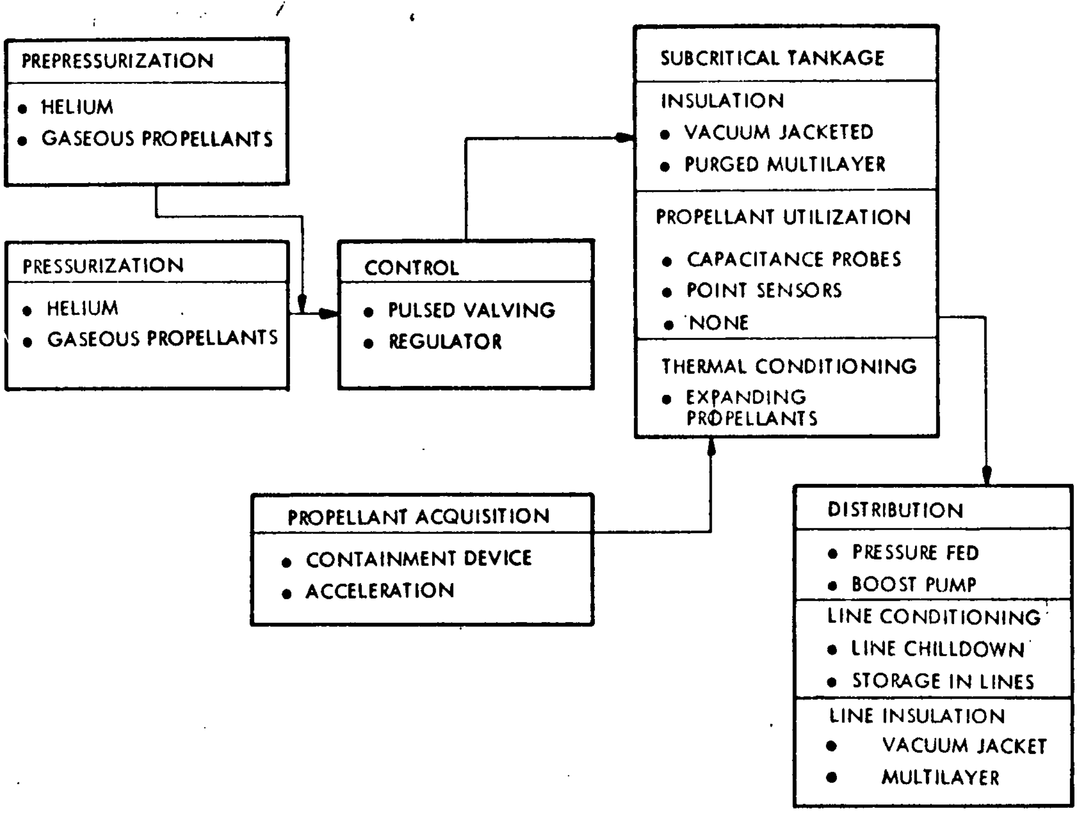

Fig. 9.1-3 Orbit Maneuvering Propellant Supply

- Prepressurization and pressurization accumulators

  If helium pressurization is used, it is assumed that the tanks are continuously pressurized.

  If gaseous propellant engine bleed is employed, prepressurization accumulators must be provided. (In an integrated system, these can be provided through the gas accumulators used for ACPS and other functions.)

- Acquisition devices for engine-restart only

  When the OMPS is evaluated as an individual subsystem, the acquisition device need only be a restart one that is filled after each start.

The selected candidate schematics are discussed in the following paragraphs:

1. Single Tanks - Pump at-the-Engine-GHe Pressurization - Propellants Lost After Engine Operation (5 and 12 dumps). The schematic for this system is presented in Fig. 9.1-4.

2. Single Tanks - Pump at-the-Engine-GHe Pressurization - Propellant Retained in the Lines (One dump) - Vacuum-Jacketed Tanks and Lines. This differs from the previous schematic only by the feedline cooling (see Fig. 9.1-4). A separate schematic is not shown. This schematic has no provisions for an initial line cooldown, since the lines will be filled on the ground prior to launch.

3. Single Tanks - Pump at-the-Engine-GHe Pressurization - Propellant Retained in the Lines (One dump) - Nonvacuum-Jacketed Tanks and Lines. This version of the concepts has line chilldown in addition to the line cooling. The schematic is not shown.

4. Single Tank - Pump at-the-Engine-GO_2/GH_2 Pressurization - Propellants Lost after Each Engine Operation (5 and 12 dumps). This schematic is quite similar to the schematics using GHe pressurization with the provisions for engine bleed. The schematic is shown in Fig. 9.1-5.

5. Single Tank - Pump at-the-Engine - GO_2/GH_2 Pressurization - Propellants Retained in the Lines - Vacuum-Jacketed Tanks and Lines. This schematic is not presented. It is the same as the previous schematic with line cooling added (see Fig. 9.1-5). There are no provisions for line childown.

6. Single Tank - Pump at-the-Engine - GO_2/GH_2 Pressurization - Propellants Retained in the Lines - Nonvacuum-Jacketed Tanks and Lines. This schematic is not presented. There are provisions for line childown.

7. Single Tank - Pump-at-the-Tank - GHe Pressurization - Propellants Lost After Engine Operation. This entire schematic is not shown. Modifications required to put the pump at-the-tank are shown in Fig. 9.1-6.

8. Single Tank - Pump at-the-Tank - GHe Pressurization - Propellants Retained in the Lines - Vacuum-Jacketed Tanks and Lines. This schematic is not presented. No provisions for line childown are required.

9. Single Tank - Pump at-the-Tank - GHe Pressurization - Propellants Retained in the Lines - Nonvacuum-Jacketed Tanks and Lines. This schematic is not presented. Provisions for line childown are required.

10. Single Tank - Pump at-the-Tank - GO_2/GH_2 Pressurization - Propellants Lost After Each Engine Operation. This schematic is Fig. 9.1-5, modified as shown in Fig. 9.1-6.

11. Single Tank - Pump at-the-Tank - GO_2/GH_2 Pressurization - Propellants Retained in the Lines - Vacuum-Jacketed Tanks and Lines. Schematic not presented.

12. Single Tank - Pump at-the-Tank - GO_2/GH_2 Pressurization - Propellants Retained in the Lines - Nonvacuum-Jacketed Tanks and Lines. Schematic not presented.

13. Dual Tanks - Pump at-the-Engine - GHe Pressurization - Propellants Lost After Each Engine Operation. Schematic presented in Fig. 9.1-7.

14. Dual Tanks - Pump at-the-Engine - GHe Pressurization - Propellants Retained in the Lines - Vacuum-Jacketed Tanks and Lines. Schematic presented in Fig. 9.1-8.

15. Dual Tanks - Pump at-the-Engine - GHe Pressurization - Propellants Retained in the Lines - Nonvacuum Jacketed Tanks and Lines. Schematic presented in Fig. 9.1-9.

16. Cascade Tanks - Pump at-the-Engine - GHe Pressurization - Propellants Lost After Each Engine Operation. Schematic presented in Fig. 9.1-10.

17. Single Tanks with Start Tanks - Nonintegrated - Pump at-the-Engine - GHe Pressurization in Start Tanks - GO_2/GH_2 Pressurization in the OMPS Tanks - Propellants Lost After Each Engine Operation. A separate schematic was not required for the evaluation of this approach. This is not a strong concept in a nonintegrated system.

18. Single Tanks with Start Tank - Nonintegrated - Pump at-the-Engine - GHe Pressurization in Start Tanks - GO_2/GH_2 Pressurization in the OMPS Tanks - Propellants Retained After Each Engine Operation. Detailed schematic not required.

19. Single Tanks with Start Tanks - Nonintegrated - Pump at-the-Tank - GHe Pressurization in Start Tanks - GO_2/GH_2 Pressurization in the OMPS Tanks - Propellants Lost After Each Engine Operation. Schematic not required.

20. Single Tanks with Start Tanks - Nonintegrated - Pump at-the-Engine - GHe Pressurization in Start Tanks - GO_2/GH_2 Pressurization in the OMPS Tanks - Propellants Retained After Each Engine Operation. Schematics not required.

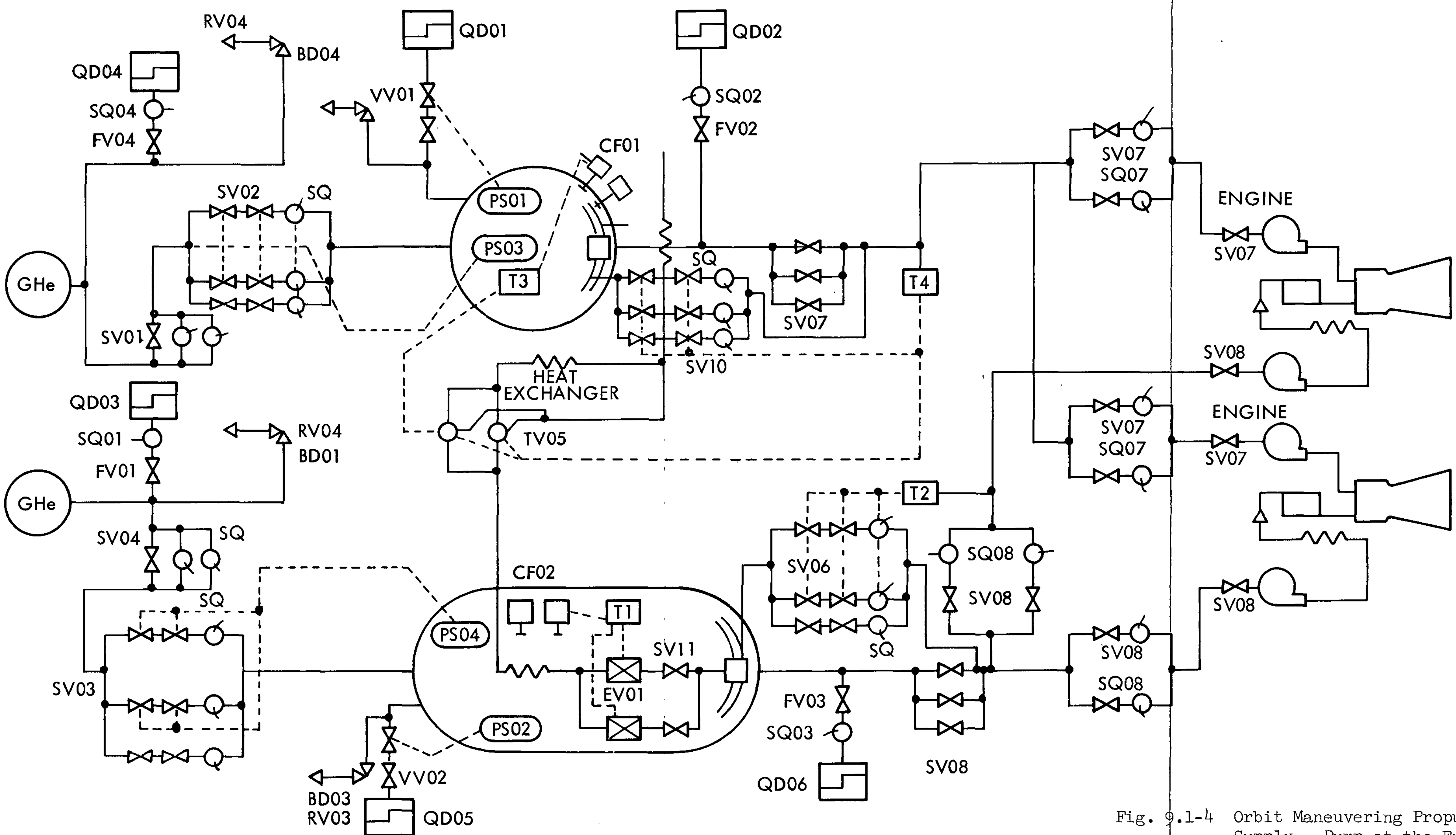

Fig. 9.1-4 Orbit Maneuvering Propulsion Supply - Pump-at-the-Engine GHe Pressurization - Propellant Lost After Engine Operation

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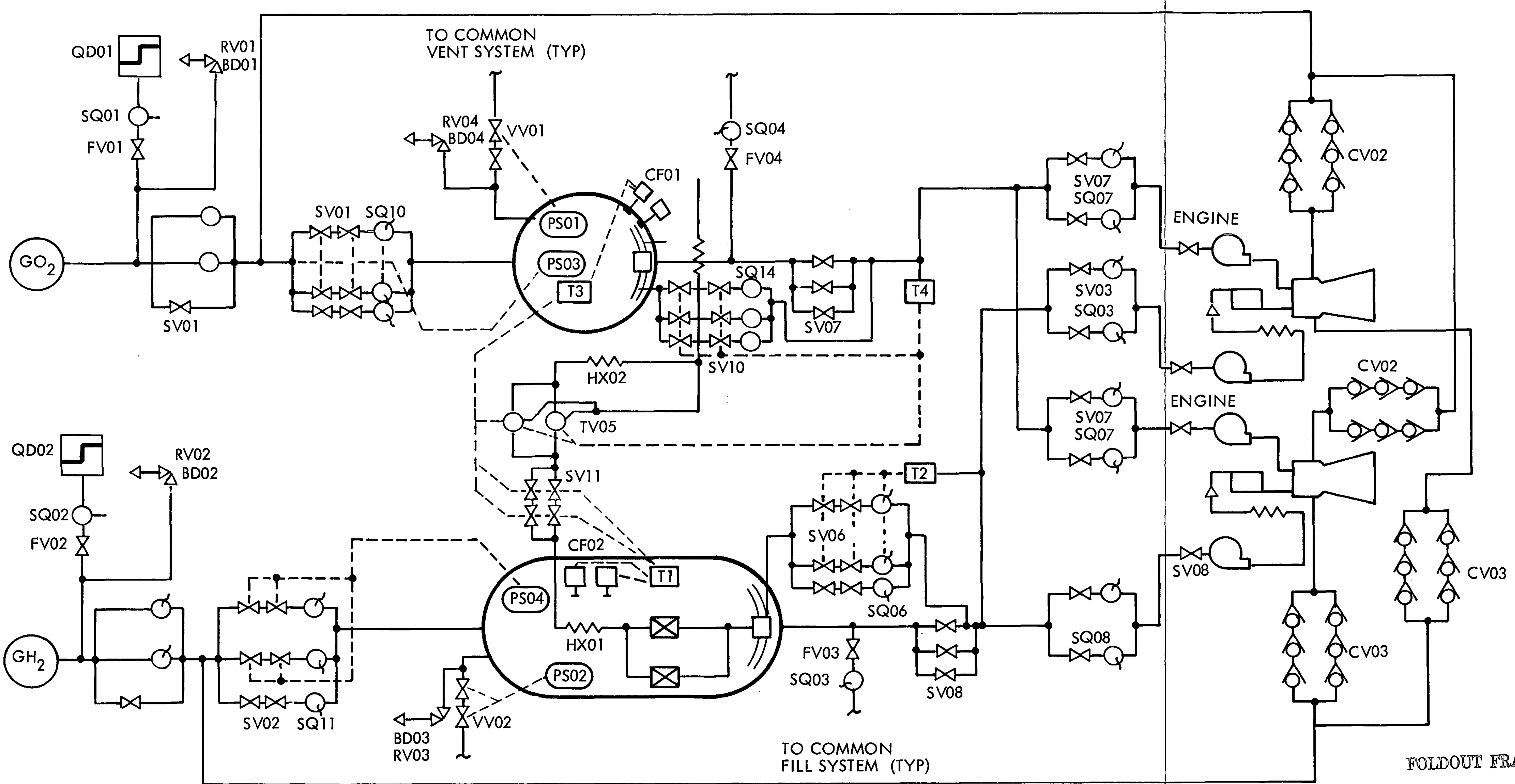

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Fig. 9.1-5 Orbit Maneuvering Propulsion Supply GO_2/GH_2 Pressurization Single Tanks, Pump-At-Engine, Propellants Lost After Engine Operating

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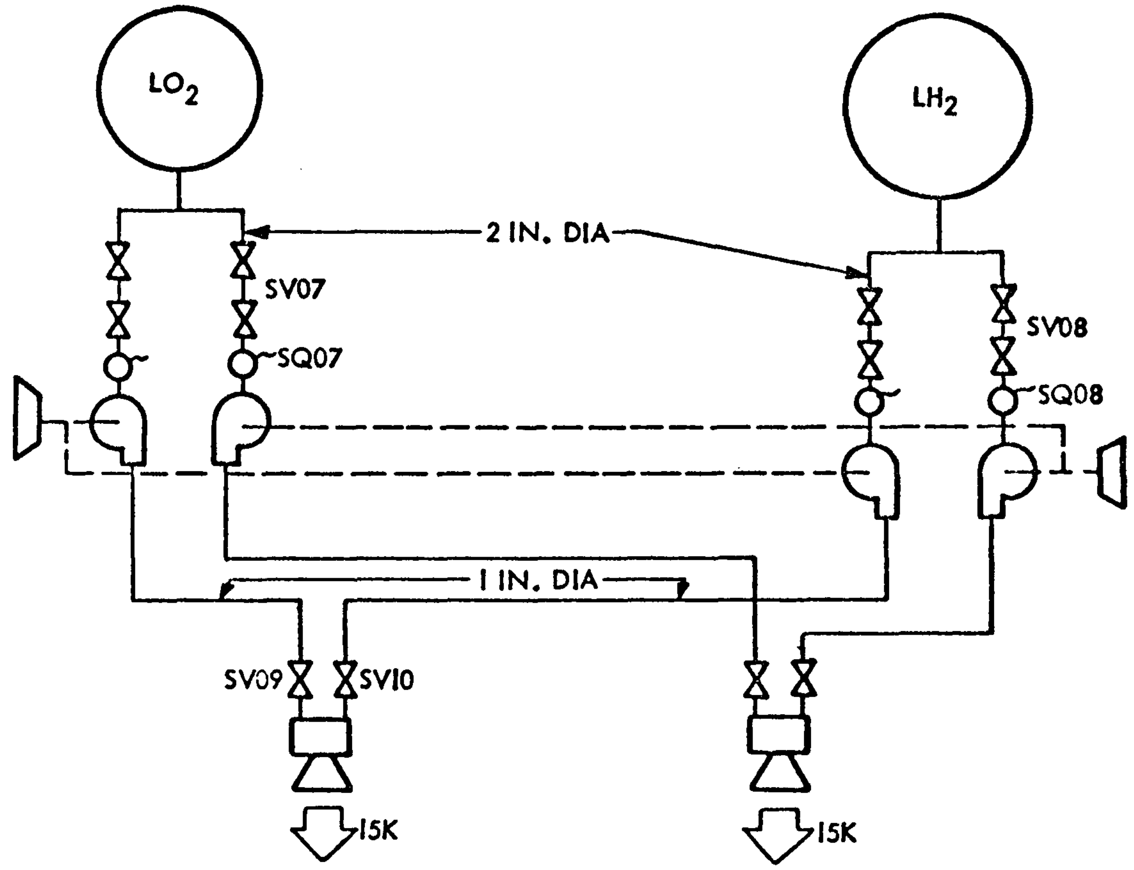

NOTE: OPTIMUM LINE DIAMETER SAME FOR DUMP CASES 1 THROUGH 12

Fig. 9.1-6 Feedline Schematic – Pumps-at-Tank

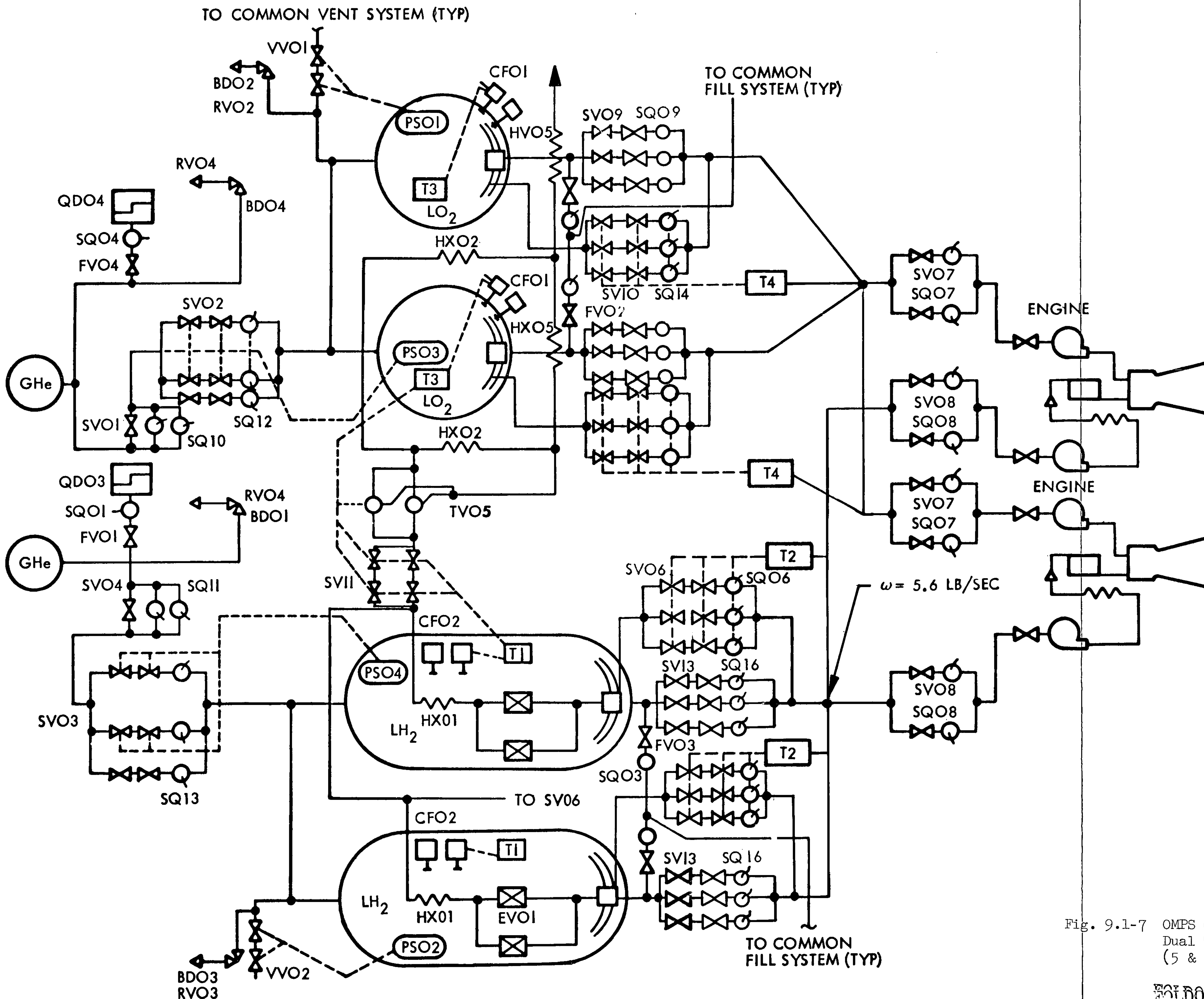

Fig. 9.1-7 OMPS GHe Pressurization Dual Tanks - Pump-At-Engine (5 & 12 Propellant Losses)

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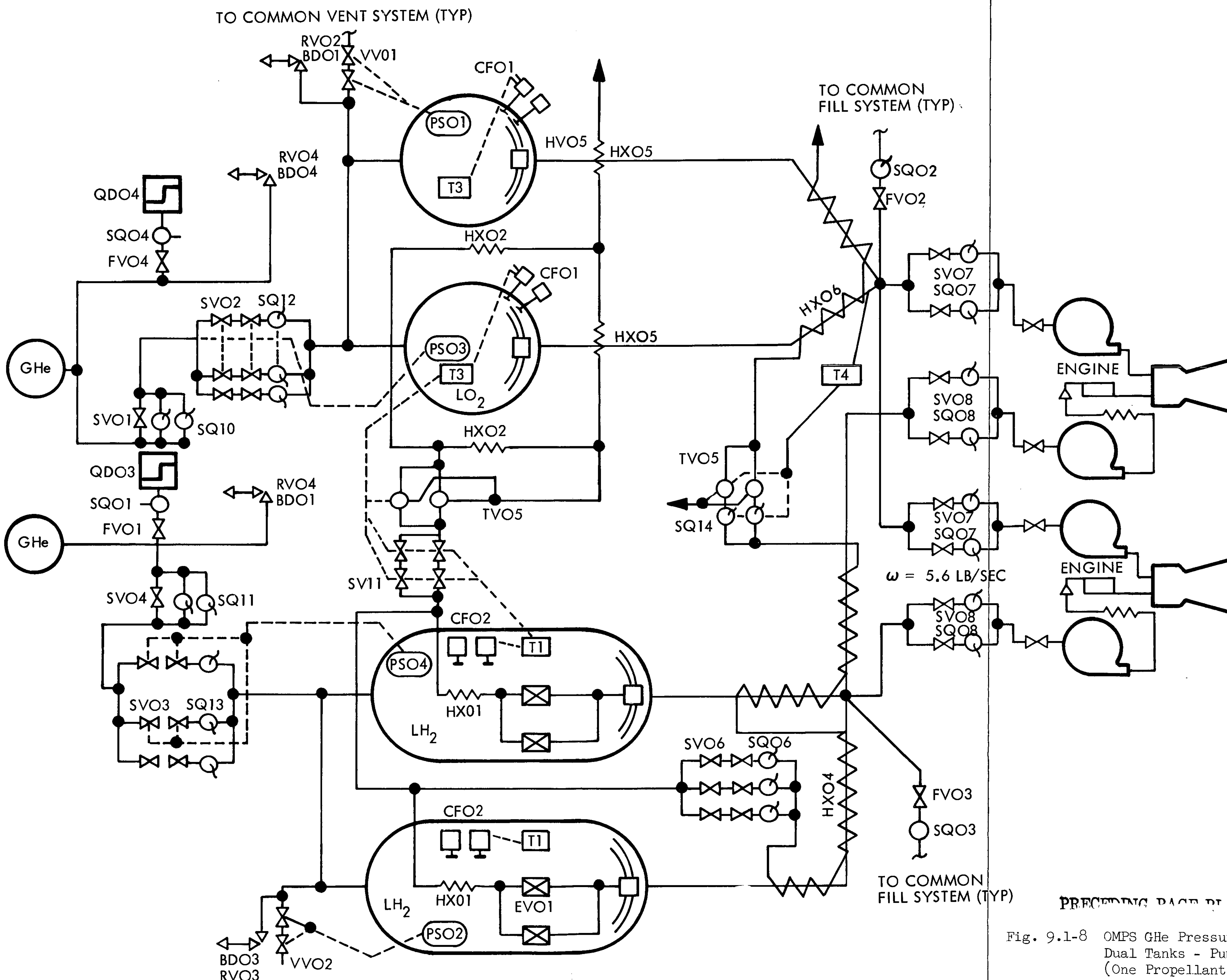

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Fig. 9.1-8 OMPS GHe Pressurization
Dual Tanks - Pump-At-Engine
(One Propellant Loss)

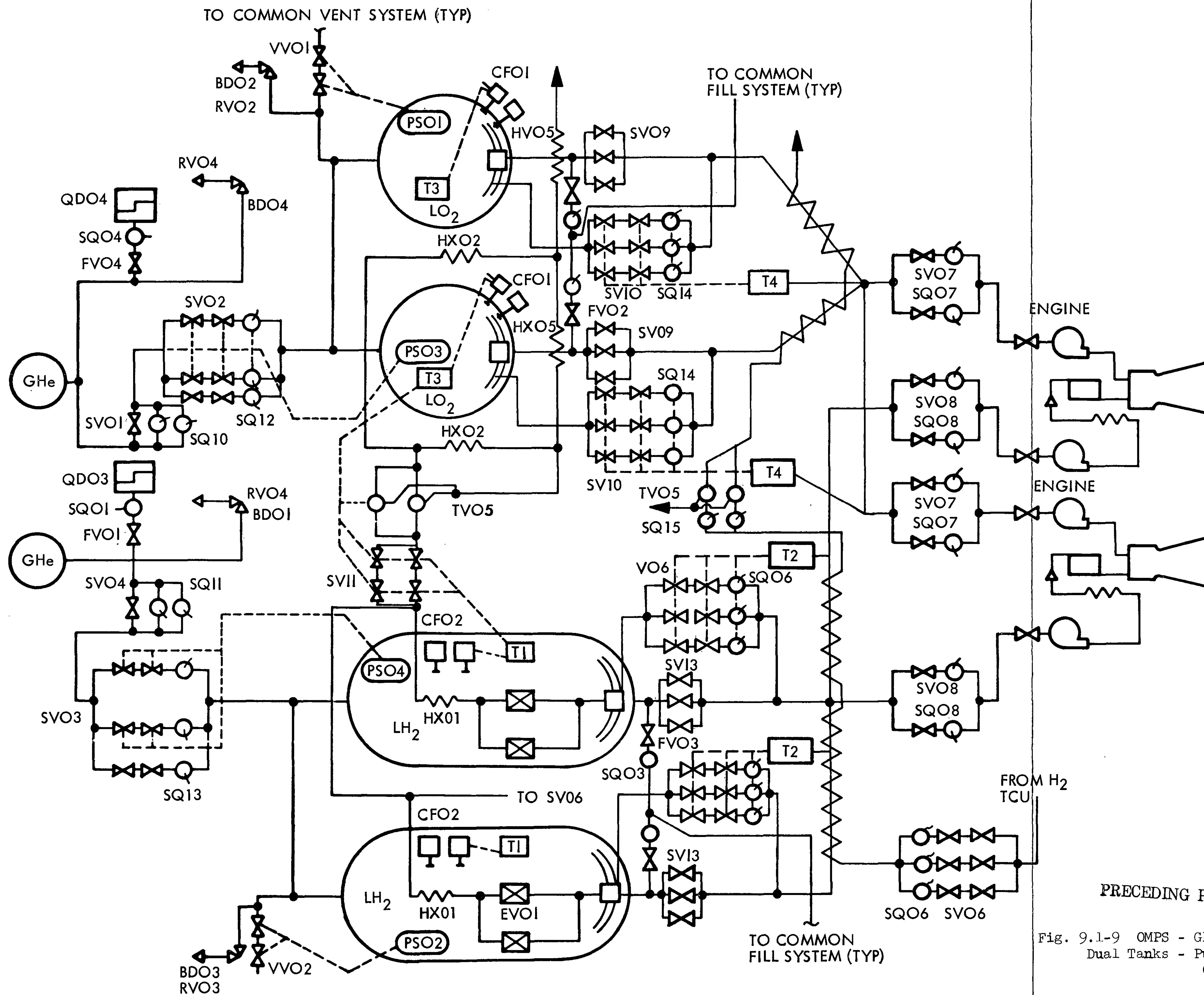

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Fig. 9.1-9 OMPS - GHe Pressurization - Dual Tanks - Pump-at-the-Engine - One Propellant Lost

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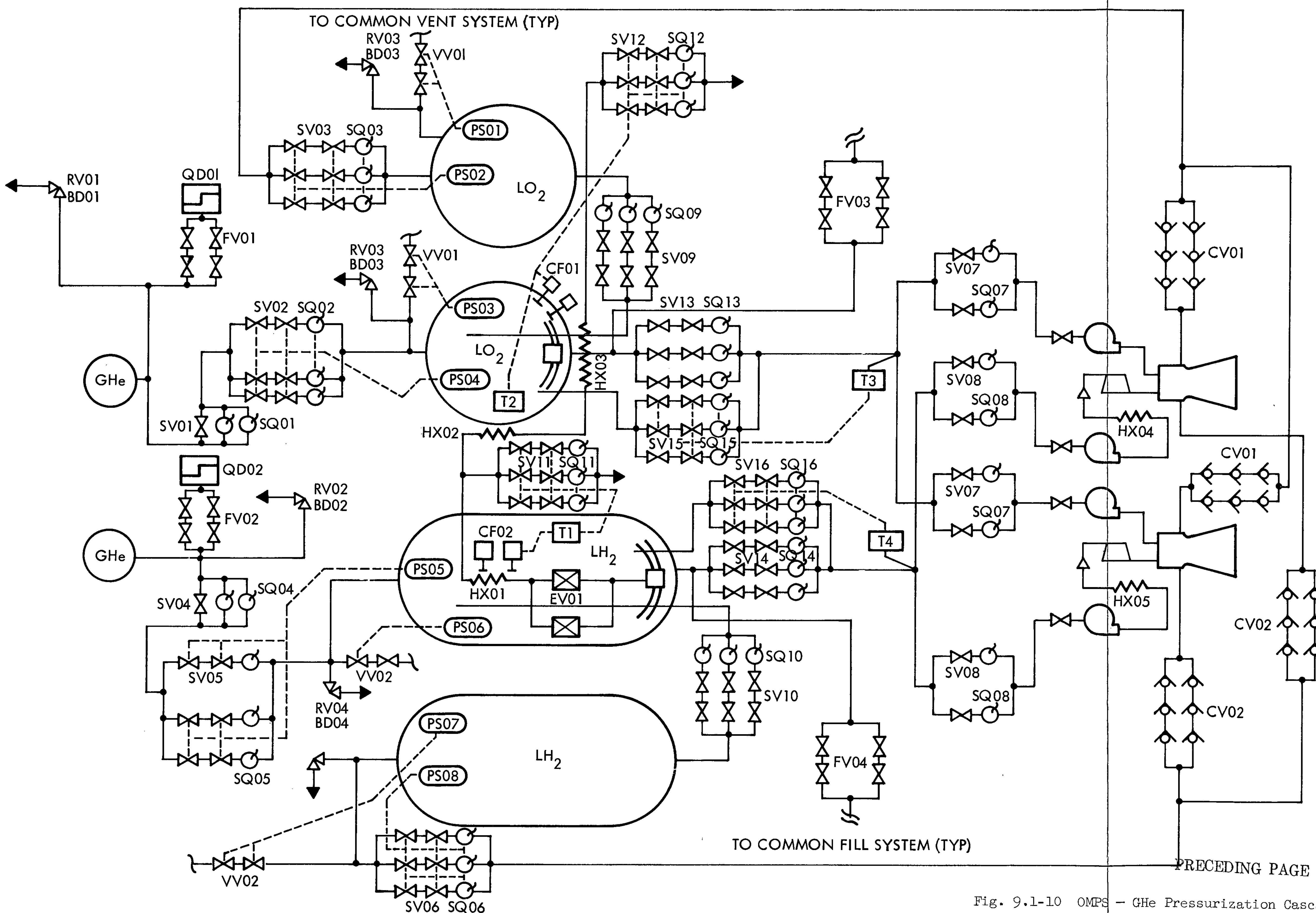

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Fig. 9.1-10 OMPS – GHe Pressurization Cascade Tanks – Pump-At-The-Engine – Propellant Lost After Engine Operation

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9.1.2 Detailed Subsystem Analyses

The analyses reported in this section are exclusive of sensitivity and tradeoff studies, which are presented in other sections. Information presented here relates to the collection of data and the evaluation of certain approaches.

9.1.2.1 Pressurization Analyses. These analyses were performed to produce parametric data of general use in the sensitivity and tradeoff studies. The resulting data is principally presented in Appendix C, along with a discussion of the procedures. Specific pressurization analyses and the application of these data were made in the tradeoff and sensitivity studies.

A comparison of the gas weights associated with helium- and oxygen-vapor pressurization of the cooled OMPS oxygen tanks indicates that the residual-vapor weights are larger for the equivalent oxygen-vapor pressurization cases. In addition, both the prepressurant and expulsion oxygen-vapor weights are greater than the helium weights.

The comparison of equivalent helium- and hydrogen-vapor pressurization of the OMPS hydrogen tanks indicates that the residual-hydrogen-vapor weights are larger for the hydrogen-vapor pressurization cases. The helium weights are greater than the sum of hydrogen-vapor prepressurant and expulsion-pressurant weights.

An important consideration is that only helium pressurization can assure that the propellants in acquisition devices are subcooled. Propellant gas pressurization results in saturation after shutdown.

Overall conclusions regarding pressurization approaches are provided in the tradeoff studies and cannot be obtained from the pressurization results alone.

9.1.2.2 Thermal Protection. The thermal protection system analyses are discussed in Appendix C. Additional thermal protection analyses were performed in the sensitivity and tradeoff studies.

9.1.2.3. Feedline Chilldown and Cooling Analyses.

9.1.2.3.1 Feedline Chilldown. If the propellants are not maintained in the feedlines by cooling, chilldown of the feedlines to the engines is required prior to several engine operations. Should a valve in the feedline open, a pressure rise can rapidly occur.

Feedline chilldown computations were performed for three basic feedline configurations: two hydrogen-feed systems and a single oxygen-feed system. Schematic diagrams of the three system configurations are shown in Figs. 9.1-11, 9.1-12, and 9.1-13; a list of the pertinent thermodynamic characteristics is shown in Table 9.1-1. The LO_2 system and the LH_2 aft system are identical, except that the LO_2 feedlines immediately downstream of each tank have different diameters.

The computation of chilldown times and mass of vaporized-chilldown propellant relied primarily on the method reported in Ref. 9-1. This method assumes that the cooldown behavior of the feedline is controlled by the resistance to the flow of boiloff gas, rather than the resistance to the transfer of heat into the fluid. In the latter case, if the flow resistance is unimportant relative to the heat-transfer resistance, the entire line could be filled with the cryogenic fluid in a short time when compared to the chilldown time. In this case, the temperature histories at all stations along the pipe will essentially coincide. The chilldown time may then be approximated by

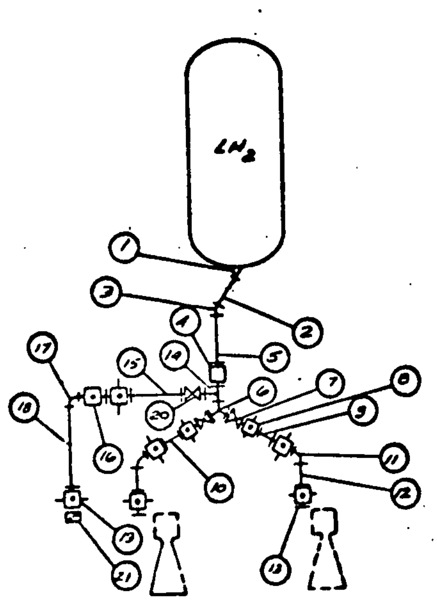
$$t_{cD} = \frac{\Delta H}{\bar{h} A_w \overline{\Delta T}}$$

where: H = total enthalpy change of the pipe material during chilldown

h = mean fluid-to-wall heat-transfer coefficient

A_w = wall area

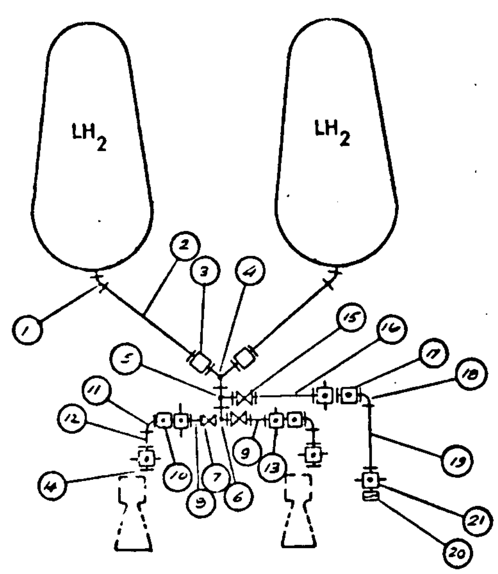
T= mean chilldown-temperature difference.



KEY

1. SUMP
2. 4 IN. LINE - 100 IN. LONG
3. 45 DEG ELBOW
4. PRESSURE VOLUME COMPENSATOR
5. 4 IN. LINE - 690 IN. LONG
6. Y-TRANSITION FITTING - 4 IN. TO 3 IN.
7. ENGINE PREVALVE (2)
8. GIMBALLED BELLOWS (6)
9. 3 IN. LINE - 100 IN. LONG
10. 3 IN. LINE - 150 IN. LONG
11. 45 DEG ELBOW (2)
12. 3 IN. SHORT LINE (2)
13. PUMP INTERFACE FLANGE (2)
14. FEED/FILL TEE
15. 2 IN. LINE - 200 IN. LONG
16. PIVOTED BELLOWS
17. 90 DEG BELLOWS
18. 2 IN. LINE - 200 IN. LONG
19. GIMBALLED BELLOWS
20. FILL SHUTOFF VALVE
21. FILL DISCONNECT

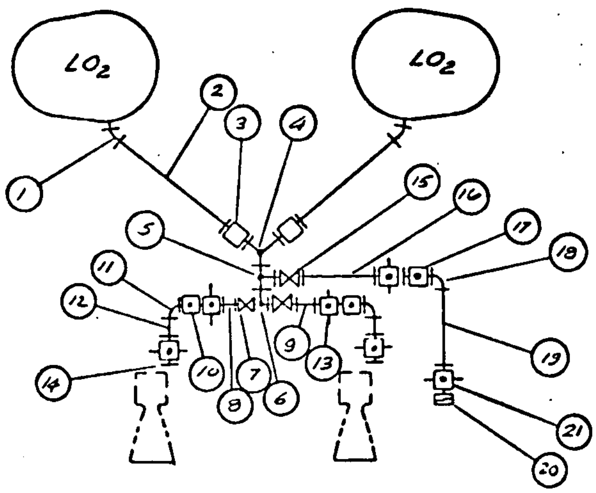
Fig. 9.1-11 Liquid Hydrogen Line Chilldown Model – LH_2 Forward



KEY:

1. 40-DEG ELBOW - (2)
2. LINE-70-IN. LONG (EXP 0.27 IN. (2)
3. PRESSURE VOLUME COMPENSATOR - (2)
4. Y-FITTING - 100-DEG THROAT ANGLE
5. FEED-FILL TEE-3 IN. TO 2 IN.
6. ENGINE FEED TEE
7. ENGINE PREVALVE - (2)
8. LINE - 75 IN. LONG (EXP 0.28 IN.)
9. LINE - 85-IN. LONG (EXP 0.32 IN.)
10. PIVOTED BELLOWS - (2)
11. 90-DEG ELBOW - (2)
12. LINE - 25-IN. LONG (EXP 0.95 IN. (2)
13. GIMBALLED BELLOWS - (4)
14. PUMP INTERFACE FLANCE - (2)
15. FILL SHUTOFF VALVE
16. LINE - 25-IN. LONG (EXP 0.95 IN.)
17. PIVOTED BELLOWS
18. 90-DEG ELBOW
19. LINE - 40-IN. LONG (EXP 0.15 IN.)
20. FILL DISCONNECT
21. GIMBALLED BELLOWS

Fig. 9.1-12 Liquid Hydrogen Line Chilldown Model – LH_2 Aft



KEY:

1. 40-DEG ELBOW - (2)
2. LINE - 70-IN. LONG (EXP 0.27-IN.) - (2)
3. PRESSURE VOLUME COMPENSATOR - (2)
4. Y-FITTING - 100-DEG THROAT ANGLE
5. FEED-FILL TEE - 3-IN. TO 2-IN.
6. ENGINE FEED TEE
7. ENGINE PREVALVE - (2)
8. LINE - 75-IN. LONG (EXP. 0.28-IN.)
9. LINE - 85-IN. LONG (EXP. 0.32-IN.)
10. PIVOTED BELLOWS - (2)
11. 90-DEG ELBOW - (2)
12. LINE - 25-IN. LONG (EXP 0.95-IN.) - (2)
13. GIMBALLED BELLOWS - (4)
14. PUMP INTERFACE FLANCE - (2)
15. FILL SHUTOFF VALVE
16. LINE - 25-IN. LONG (EXP. 0.95-IN.)
17. PIVOTED BELLOWS
18. 90-DEG ELBOW
19. LINE - 40-IN. LONG (EXP. 0.15-IN.)
20. FILL DISCONNECT
21. GIMBALLED BELLOWS

Fig. 9.1-13 Liquid Oxygen Chilldown Model — LO_2 Aft

Table 9.1-1

OMPS FEED SYSTEM CHARACTERISTICS

Configuration	Average Flow Area ($in.^2$)	Initial Temperature (R)	Initial Propellant Sat. Pressure (psia)	Chilldown Enthalpy Change Required (Btu)
LH_2 Forward	2.91	500	18	2,764
LH_2 Aft	7.06	500	18	2,173
LO_2	5.76	500	18	1,979

Notes: (1) All lines are 2219 T87 Aluminum Alloy, 0.025-in. wall thickness.

(2) Fittings, bellows, and valves are 321/347 stainless steel.

The opposite extreme, termed a flow-controlled childown, is that in which the resistance to heat flow is very small. In this case, the pipe temperature at a given point will drop instantly to the liquid temperature as soon as the liquid reaches that point. The progress of the cold front along the pipe is controlled by the rate at which the boiloff gas can be forced out of the pipe end. The details of the childown computation for this case are explained in Ref. 9-1.

In applying the simplified analysis method, it was assumed that the thermal mass of the elements making up the feed system (valves, lines, bellows, etc.) was uniformly distributed along the line.

Estimates of peak surge pressure for both unrestricted lines and lines containing inlet and outlet restrictions were obtained using the data of Refs. 9-2 and 9-3.

Results of the basic childown calculations are shown in Table 9.1-2. The computed childown times for all the configurations are very small; however, the vaporized-propellant masses are appreciable. The addition of inlet- and exit-flow restrictions (orifices), to simulate the addition of small-diameter bypass lines, produces an increase in childown time with a small reduction in childown propellant mass. Peak surge pressures can be very high - up to six times the inlet pressure with LO_2.

The effect of the addition of an inlet-flow restriction is illustrated in Fig. 9.1-14. Rapid reduction in peak surge pressure with decreasing inlet orifice diameter indicates that the use of a small-diameter bypass line could provide the necessary cooldown flow while limiting pressure surges to very low values.

Table 9.1-2

RESULTS OF FEEDLINE/CHILLDOWN COMPUTATIONS

Feed System Configuration	Mean Line Diameter (in.)	Inlet/Outlet Orifice Diameters (in.)	Chilldown Time (sec)	Chilldown Propellant (lb)	Estimated Max Surge Pressure (psia)[1]
LH_2 Forward	1.50	None	5.1	15.1	75.0
LH_2 Forward	1.50	0.50/0.50	22.7	14.6	30.5
LH_2 Aft	3.00	None	2.8	26.2	75.0
LH_2 Aft	3.00	1.00/1.00	12.5	22.0	30.5
LH_2 Aft	1.00	None	4.2	3.9	75.0
LH_2 Aft	1.00	0.25/0.25	~70	3.8	28.5
LO_2	2.71[2]	None	5.0	32.0	150.0
LO_2	2.71[2]	0.25/0.25	31.3	28.0	29.0
LO_2	1.00	None	6.1	8.2	150.0
LO_2	1.00	0.125/0.125	~300	7.9	30.0

Notes: (1) Inlet Pressure = 25 psia
(2) Upstream Line Diameter = 2.00 in.

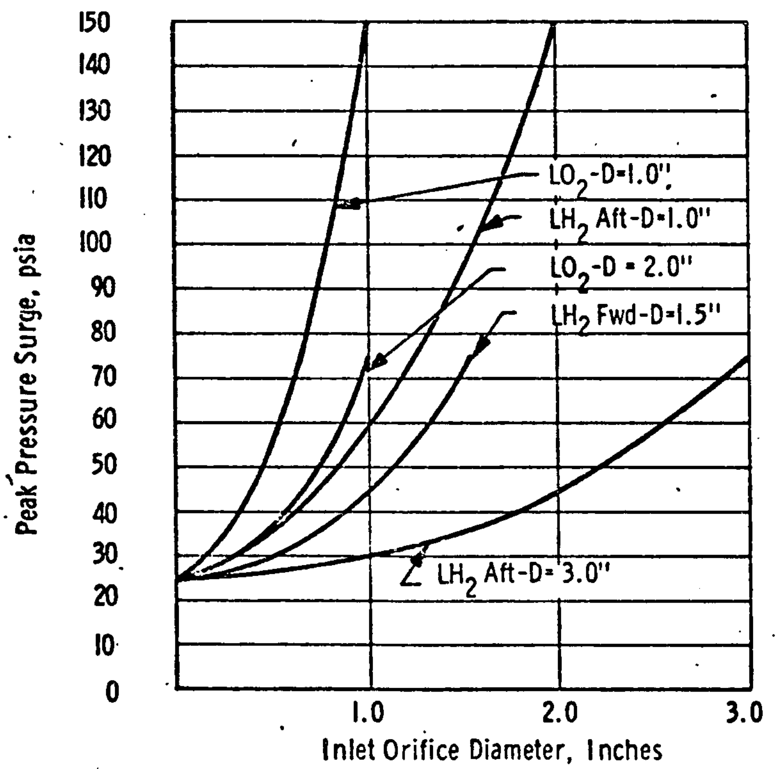


Fig. 9.1-14 Effect of Inlet Flow Restrictions on Surging

9.1.2.3.1 Feedline Cooling. If the propellants are left in the feedlines (for cases when only one loss of propellant feedlines is planned), feedline cooling is necessary to intercept heat leakage. Feedline cooling may be performed by hydrogen cooling or by circulation of propellants.

Evaluations have been made of the requirements of hydrogen for feedline cooling. A summary of these requirements is presented in Table 9.1-3. Note that requirements for continuous cooling are in the same order-of-magnitude as that required for five chilldowns prior to start, as presented in Table 9.1-2.

Also, evaluations were made of feedline cooling by recirculation of propellants. The parameters considered included:

a. Feedline length and diameter (typical of the NAR and MDC vehicle configurations).

b. Feedline and circulation-line insulation (NRC-2) thicknesses (1/2 in. on feedlines with 1/4 in. on circulation lines, and 1 in. on feedlines with 1/2 in. on circulation lines).

c. Engine heat-leak rate (10 Btu/hr and 20 Btu/hr per fluid per engine).

d. Circulation flowrate.

Major heat leak sources into the feedline system include: through the feedline insulation, from the engine, and through the circulation-line insulation. Heat leak through valves and other components is considered to be minimal through the use of insulated covers with very small heatleaks.

The total temperature-rise sensitivities to the various feedline system parameters are shown in Figs. 9.1-15 through 9.1-18 for both vehicle configurations and both propellants. Also shown in each figure is (1) a sketch of the system layout with the circulation lines included; and (2) in tabular form, the total energy returned back to the storage tanks over a 168-hr mission. This energy must be extracted, if a H_2 thermal control unit is used. In most cases, the H_2 vented from the LH_2 tanks is more than sufficient to cool the LO_2 tanks (each pound of H_2 used to cool the LH_2 tanks contains about 144 Btu of cooling capability for the LO_2 tanks).

Table 9.1-3

FEEDLINE COOLING REQUIREMENTS

Tankage	Pump Location	Transient	Prop.	Line Dia.(in.)	Prop. in Feedlines (lb)	Cooling Hydrogen Req.
Single Tank	Pump at Engine	RL-10	LO_2	3	52	(30) Zero
			LH_2	4 1/2	6	110
	Pump at Tank	RL-10	LO_2	1	6	(22) Zero
			LH_2	1	0.5	55
Dual Tank	Pump at Engine	RL-10	LO_2	2/3	50	(55) Zero
			LH_2	3/3	5	132
Cascade Tanks	Pump at Engine	RL-10	LO_2	3	52	(30) Zero
			LH_2	4	7	122
Single Tank	Pump at Engine	New	LO_2	2 1/2	36	(28) Zero
			LH_2	3 1/4	5	68
	Pump at Tank	New	LO_2	1	6	(22) Zero
			LH_2	1	0.5	55

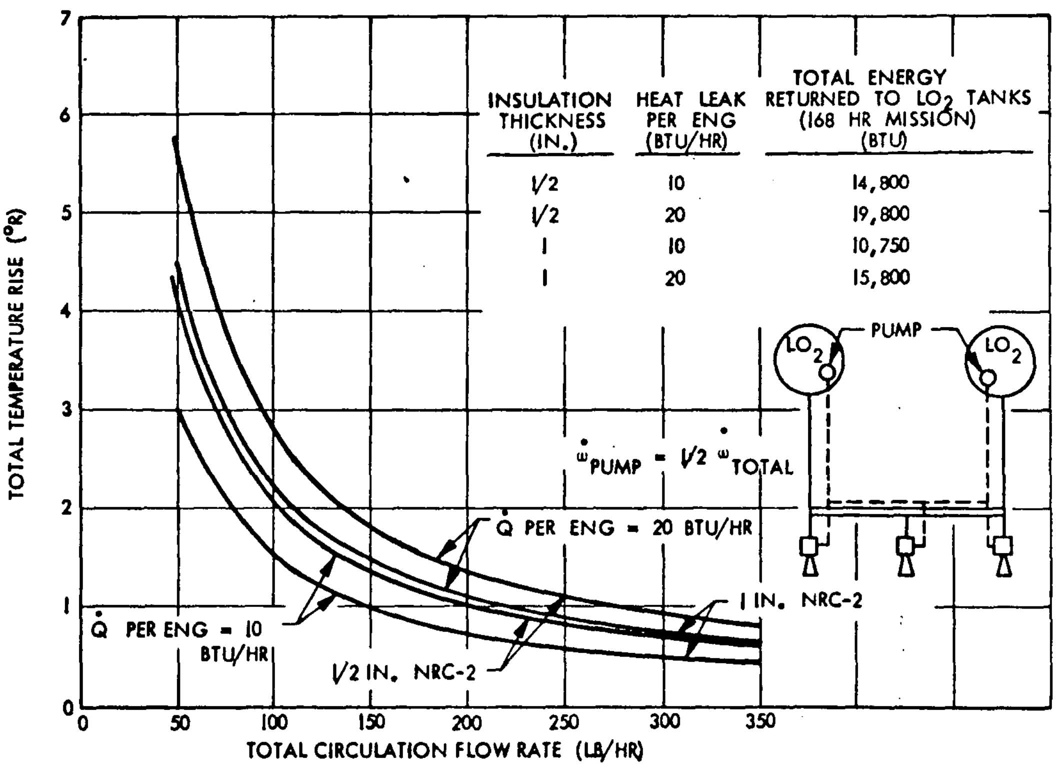


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Fig. 9.1-15 OMPS Feedline Circulation Flow Effects — NAR LO_2 System (3 Engines)

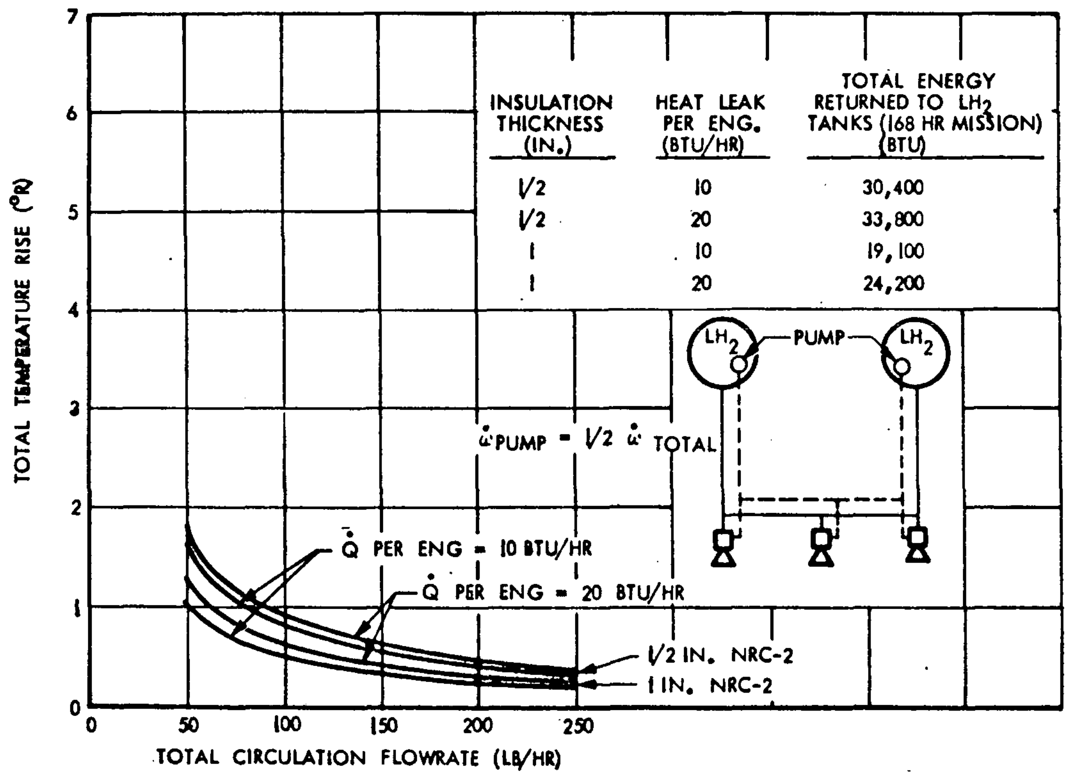

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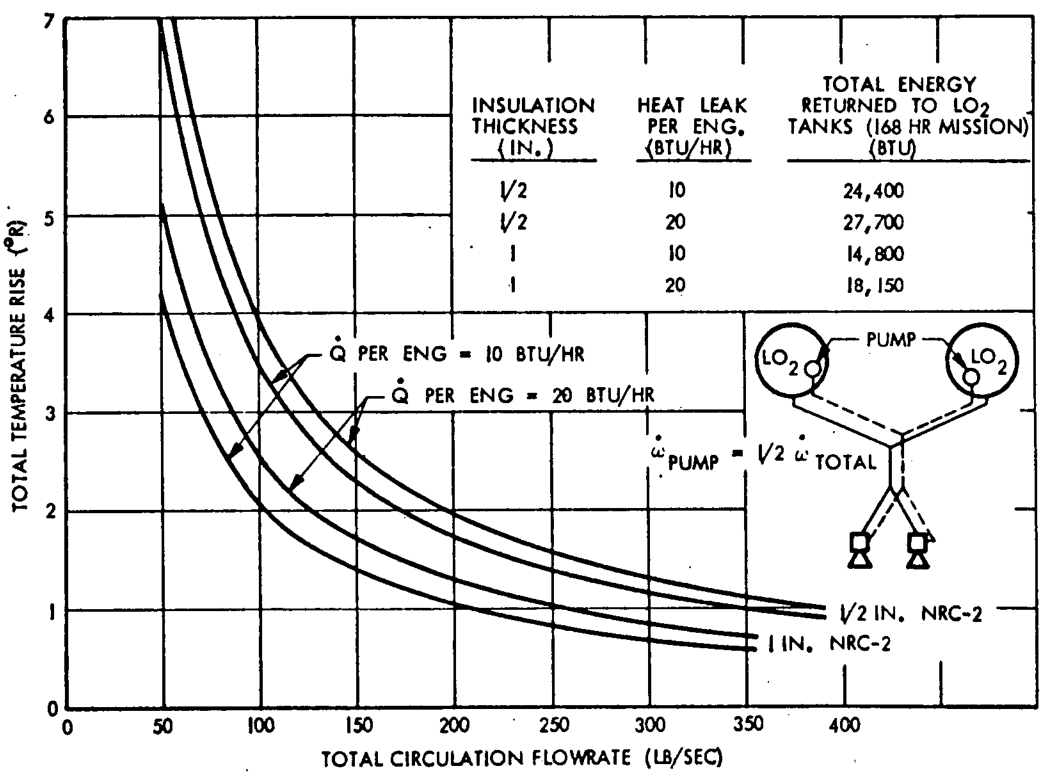
Fig. 9.1-16 OMPS Feedline Circulation Flow Effects — NAR LH_2 System (3 Engines)



D03798

Fig. 9.1-17 OMPS Feedline Circulation Flow Effects – MDC LO_2 System (2 Engines)

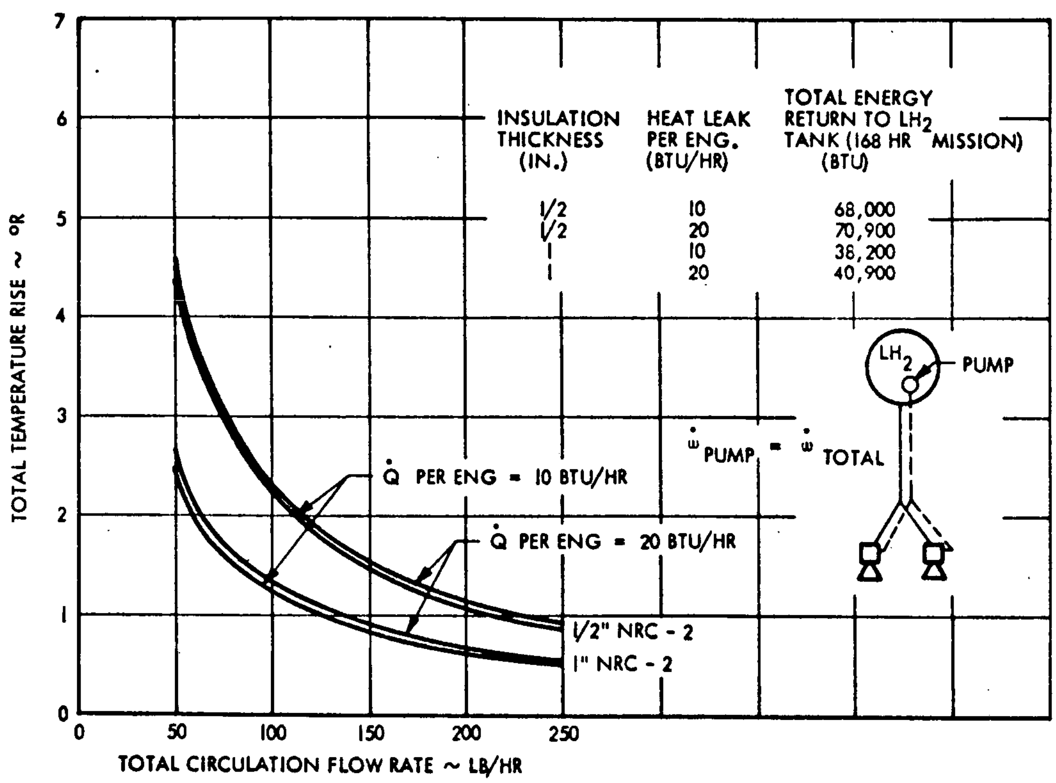


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Fig. 9.1-18 OMPS Feedline Circulation Flow Effects – MDC LH_2 System

Pump power requirements for these low-flowrates with the resulting low-pressure drops are negligible (less than 1 hp) and, thus, were not plotted.

9.1.2.4 Propellant Acquisition. When the Orbit Maneuvering Propulsion Supply is not part of an integrated system, the propellant acquisition components need only to provide liquid feed for the limited period of time required for liquid orientation in the tanks, as dictated by vehicle acceleration. This type of system can be termed a "partial retention" or "restart" device.

A design concept for a restart type of propellant acquisition device is presented in Fig. 9.1-19. Dimensions of the device are normalized to the tank diameter. The device employs a technique developed by LMSC for compounding the capillary strength of woven screen material. This technique is discussed in more detail in Appendix B - Propellant Acquisition; the device shown has been scaled to provide for the start transients for the RL-10-3-3 engine.

This restart concept incorporates a combined hydrostatic and momentum venting system. The vent tube promotes expulsion of the gas and vapor drawn into the restart volume during the OMPS engine-start transient and bulk propellant-settling period. Potential for refill originates from the dynamic pressures of the incoming settling bulk propellants. This type of vent and refill system is necessary, because the upsetting accelerations due to ACPS operation are very nearly equal to study OMPS accelerations available for hydrostatic refill (see Table B-1 in Appendix B). The refill feature makes this design independent of the number of restarts and any other restrictions due to engine-duty cycle.

Data regarding propellant acquisition devices in integrated systems are presented in section 9.3 and Appendix B.

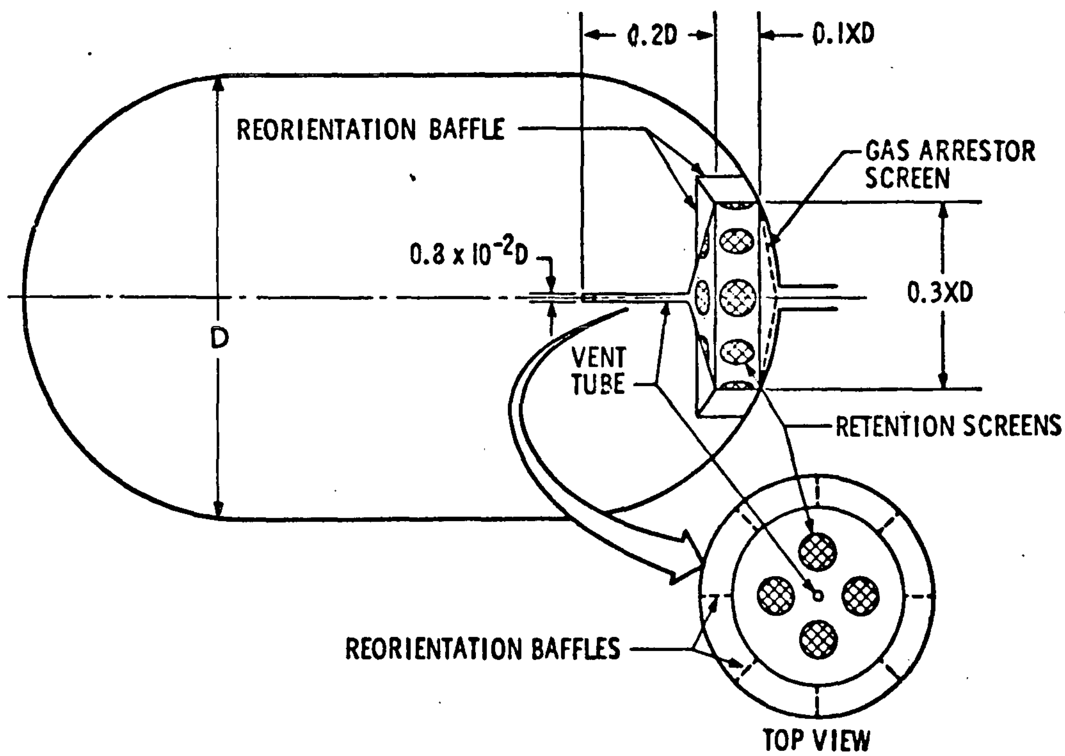


Fig. 9.1-19 Typical Acquisition Device For Engine Restart

9.1.2.5 Propellant Utilization. Propellant utilization was evaluated for systems integrating the storage of the Orbit Maneuvering propellant and the Attitude Control propellant into combined storage tanks. This was considered to be the principle problem associated with propellant utilization in the Orbit Maneuvering propulsion subsystem. The results of these analyses and evaluations on the integrated system are presented in Section 10 of this report. It was not considered necessary to repeat these results in this section of the report.

The propellant utilization problem in the non-integrated Orbit Maneuvering Propellant Supply is not a very significant problem, as can be determined by examination of the data in Section 10. The RL-10 engines (or any of the advanced engines under consideration) have a mixture ratio control capability. The approach to assuring the most effective utilization of all of the propellant would be to examine all of the possible errors in loading and mixture ratio control, and to provide a sufficient hydrogen fuel basis to assure the utilization of all of the oxygen.

When the propellants for the non-integrated Orbit Maneuvering Propellant Supply are being used, the tanks are under axial acceleration, and a capacitance type liquid level indicator is effective. Also, whenever the vehicle is accelerated axially by the attitude control, the propellant levels can be measured. Therefore, a requirement was not identified for a zero-gravity propellant quantity measuring gage. Any leakages from the storage system could be monitored by other sensors, which would be more effective than through monitoring of the propellant quantities.

9.1.3 Sensitivity Studies

Sensitivity studies, conducted for the Orbit Maneuvering Propulsion Supply subsystem, evaluated a number of design and technology areas. These were as follows:

- Thermal Protection
- Thermal Conditioning
- Line Size, Start Transients, and Feedline Propellant Recovery
- Cascade Tank

9.1.3.1 Thermal Protection Sensitivity Studies. A sensitivity study was performed to compare the overall effects of various insulation systems and to provide insulation weight information for the tradeoff studies. To obtain information on all tankage arrangements, the following were examined for 168-hr missions:

- Single H_2 tank, Single O_2 tank
- Single H_2 tank, Dual O_2 tanks
- Dual H_2 tanks, Dual O_2 tanks

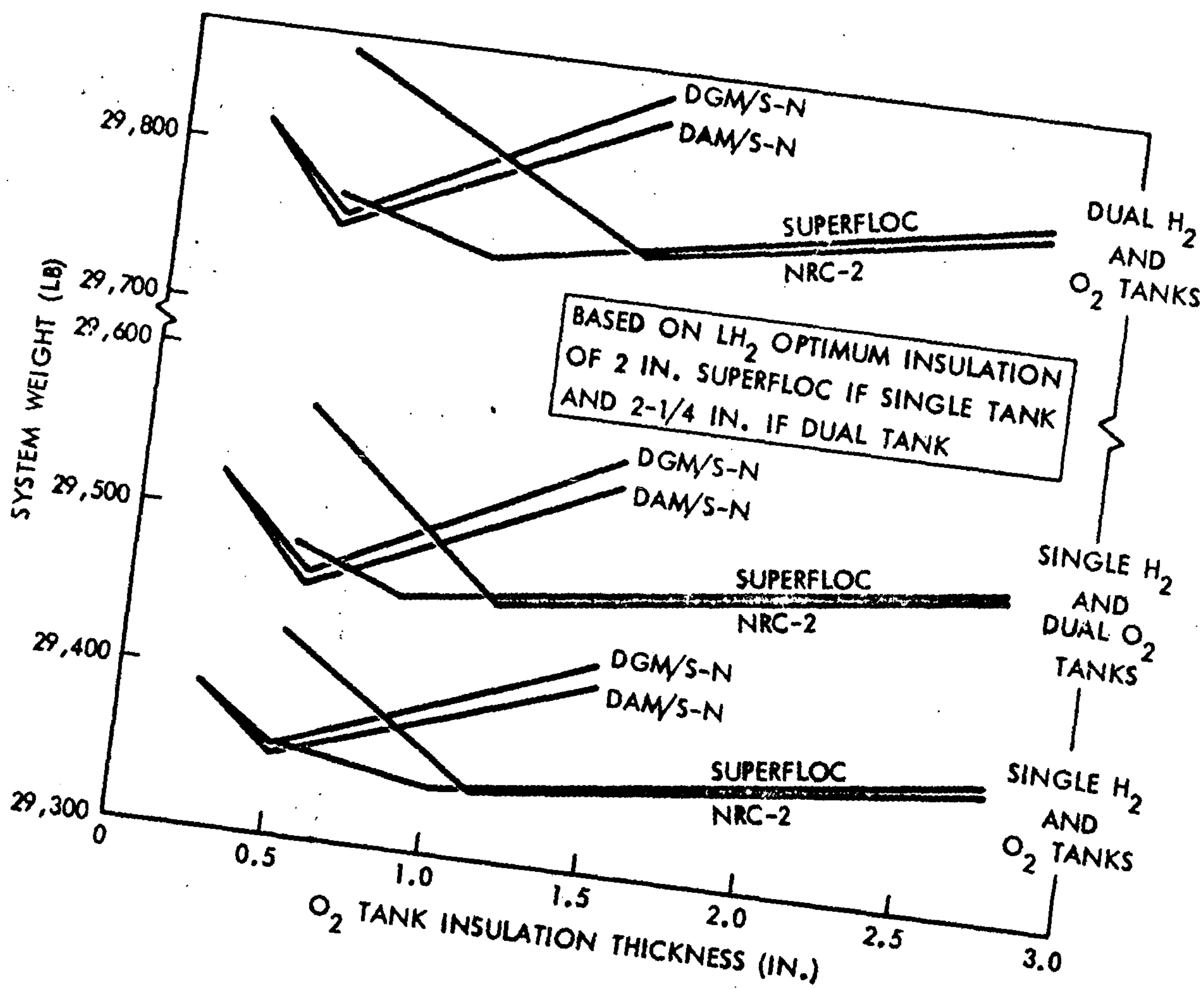
The optimum system was considered to be that arrangement and combination of tank insulations, which results in the minimum combined-weight summation of the stored LH_2 and LO_2, storage tanks, tank insulations, and tank vacuum jackets.

For each storage arrangement, a type and thickness of insulation was determined for the LH_2 storage tank(s), which resulted in minimum LH_2 system weight for the mission - considering tank, insulation, and jacket weight and LH_2 boiloff weight. Studies were performed for a range of thicknesses of double-aluminized Mylar/Silk net, double goldized Mylar/Silk net, NRC-2, and Superfloc each at its most advantageous practical layer density. A 2-in. thickness of Superfloc was found to result in minimum weight for a single LH_2 tank, and 2-1/4-in. Superfloc for the dual LH_2 tanks.

For the LO_2 tank(s), the same range of insulation types and thicknesses was investigated. The resultant tank heat gain in each case was compared with the cooling effect available in the LH_2 boiloff from the minimum-weight LH_2 system; the additional LH_2 vent quantity required to cool the LO_2 was then determined for each case, and the incremental effect upon LH_2 tank, insulation, and jacket weight was calculated. For each type and thickness of LO_2 tank insulation, a combined weight was computed for the LH_2 and LO_2 storage system. Checks were made to confirm that the minimum-weight LH_2 system results in the lowest combined-system weight.

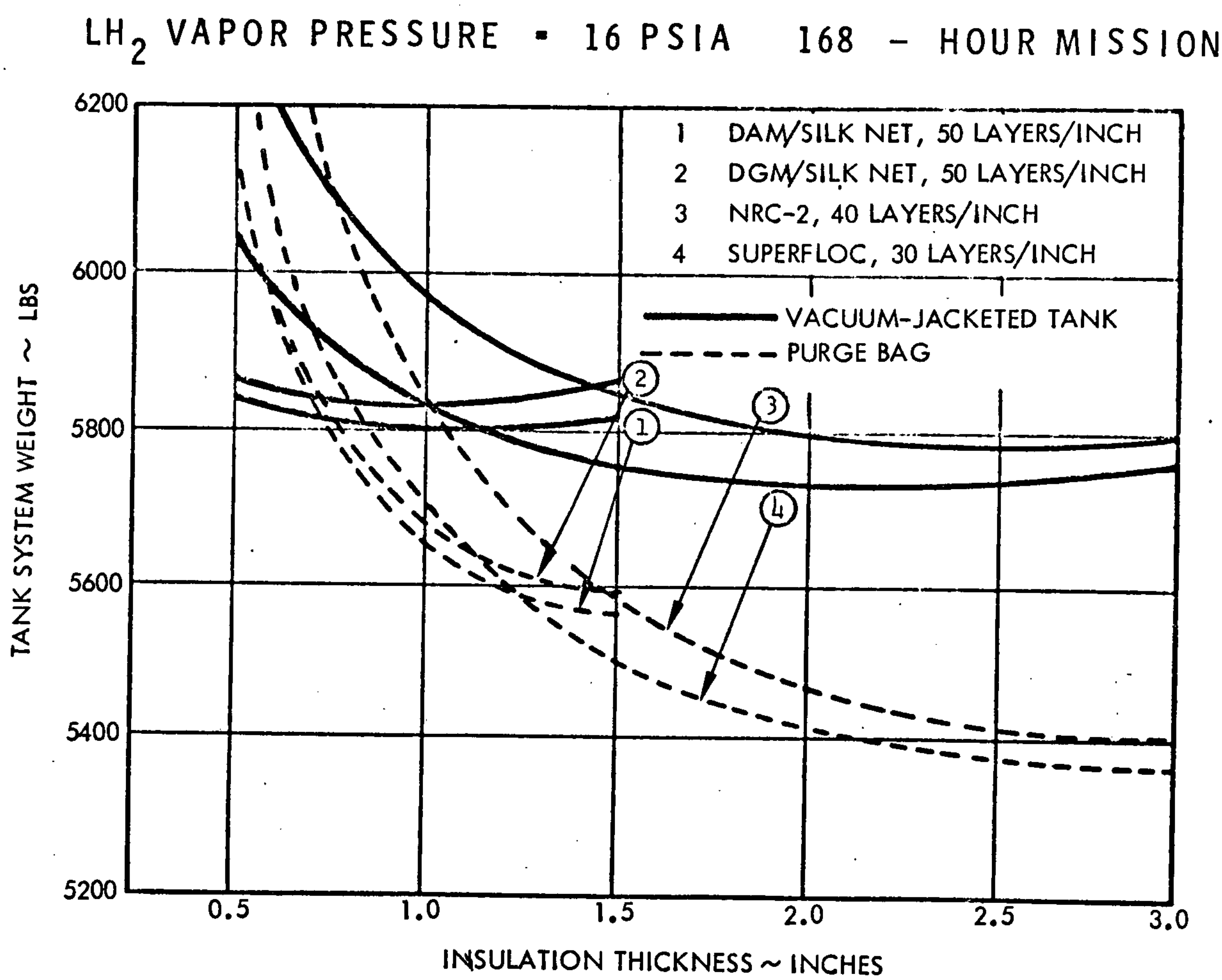
Figure 9.1-20 shows the results of the study. For each tank arrangement and for each type of LO_2 tank insulation considered, the combined-system weight is plotted versus the thickness of LO_2 insulation. Note from the figure that the minimum combined-system weight for any of the tank arrangements is insensitive to the type of LO_2 insulation used. The effect of tank arrangement is pronounced, with approximately a 400-lb difference between the dual LH_2/dual LO_2 tank arrangement and the single LH_2/single LO_2 tank arrangement. A less severe difference is seen to occur between the dual tank arrangement and the single H_2/dual O_2 tank system.

Also, sensitivity studies were conducted to determine the penalties for vacuum-jacketing and the effects of insulation types as related to the vacuum jackets. To obtain data as a function of tank pressure, two maximum vapor pressures were examined. The comparisons include the boiloff from heat added during ascent. The results also include the helium required for insulation purging and the purging system weight. The results of the evaluations are presented in Figs. 9.1-21 and 9.1-22. As may be seen, the penalty associated with the vacuum jackets for nonintegrated tanks is approximately 400 lb. (The penalty for the larger tanks in integrated systems is considerably larger.)



D02979

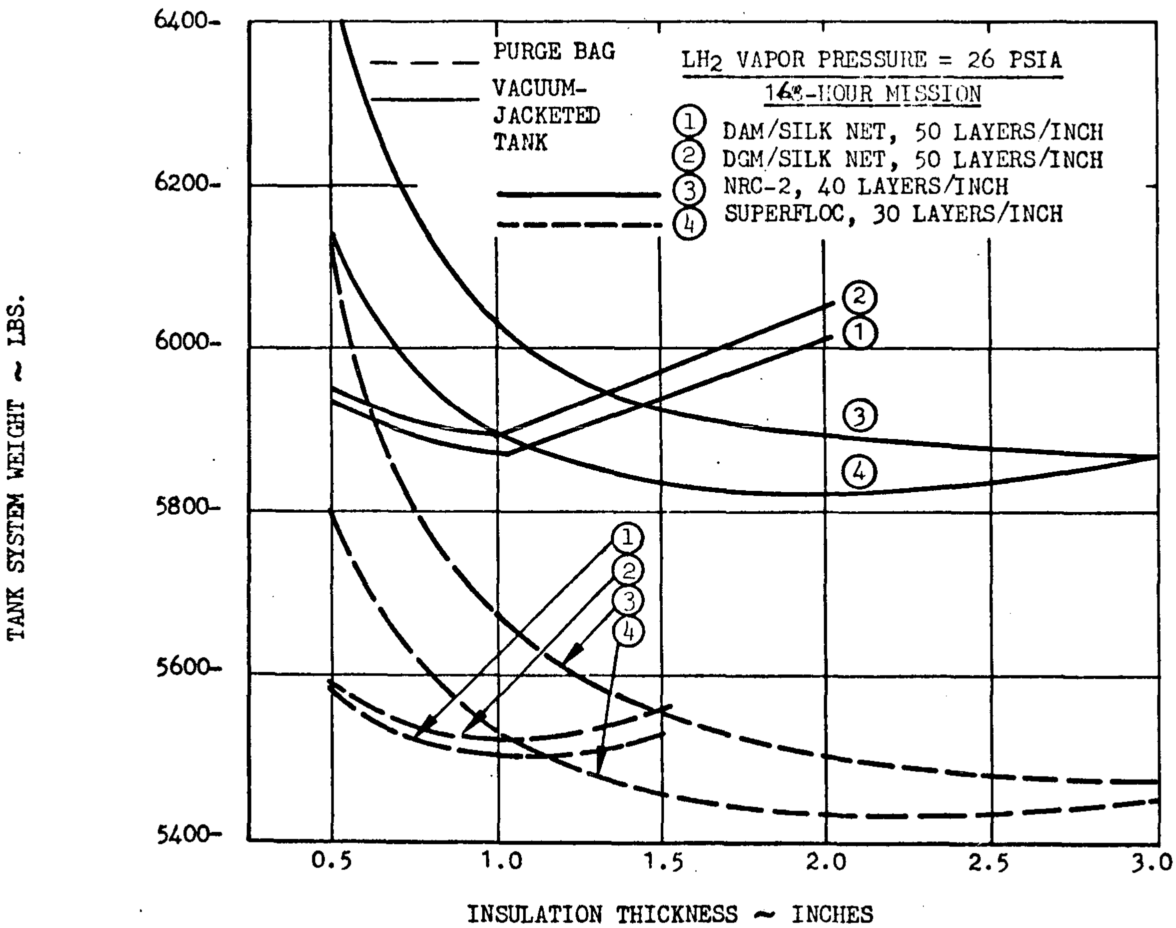
Fig. 9.1-20 OMPS Propellant Storage System Comparison (168-Hour Mission)



D02647

Fig. 9.1-21 Tank System Weight Vs Thickness Of Insulation For Vacuum-Jacketed And Purge Bag Configurations

C3



D02637

Fig. 9.1-22 LH_2 Tank System Weight Vs Thickness Of Insulation For Vacuum-Jacketed And Purge Bag Configuration

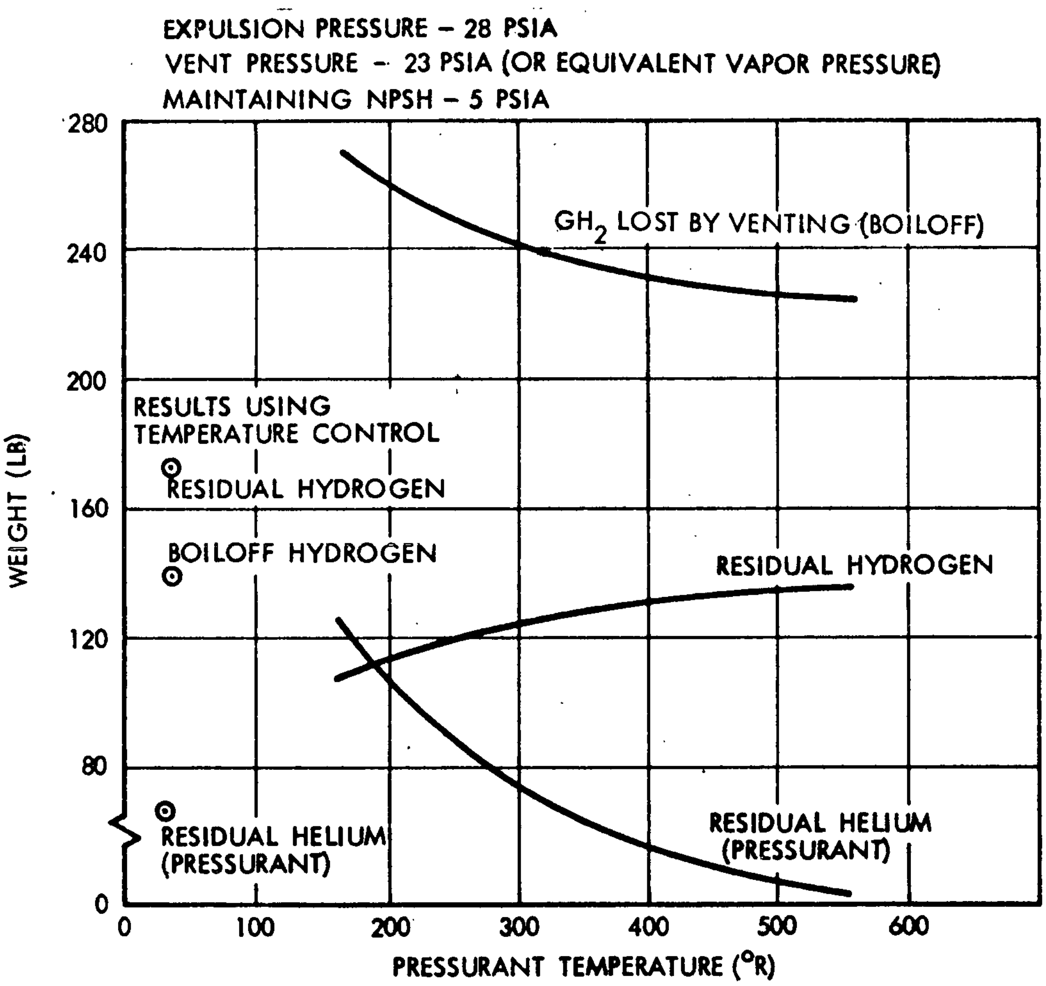
9.1.3.2 Thermal Conditioning Studies. The vapor pressure in the OMPS LH_2 tank should be maintained with a thermal conditioning unit, which expands the propellants and cools the hydrogen with a heat exchanger. In a system pressurized with GH_2, the vapor pressure can be maintained through the use of a pressure regulator or pressure switch that allows venting within a pressure band. However, in a hydrogen tank pressurized with helium, any pressure rise will be indicated to be vapor pressure rise, and if pressure is being used as the control, then, the tank will be vented by the thermal conditioning unit. Accordingly, control of vapor pressure by use of the liquid temperature and vapor pressure relationships is a desirable approach. The liquid temperatures would be the control points and venting would be based on temperature rise above an upper band. Then, tank pressure control can be separated from liquid-vapor pressure control.

An example of the effects of pressurization to a given pressure for expulsion, followed by venting at a lower pressure, is presented in Fig. 9.1-23. The use of pressure control for venting will continue to drive the vapor pressure down with resulting penalties. Results of using temperature control for venting is shown. Overall savings result from the use of temperature control.

9.1.3.3 Line Size, Start Transients, and Feedline Propellant Recovery Studies. Historically, cryogenic propulsion systems have been significantly affected by engine-start transients and the resulting line sizes, line losses, and tank pressure effects. The RL-10 engine-start transient, which is very severe, and a more desirable nominal turbopump engine-start transient were employed in the evaluations; characteristics are presented in Section 5.

The following factors influencing weight were included in the tradeoffs:

- Line weight
- Tank weight (compared to baselines)
- Pressurizing gas weight (helium used in all cases)
- Pressurizing gas storage weight
- Propellant losses in line residuals



D02967

Fig. 9.1-23 Effects Of Pressure Control Approach On OMPS LH_2 Tank

The sensitivity examinations are designed to indicate the following:

- Effects of start transients
- Effects of the number of losses of the propellants in the lines, as a function of line size
- Probable optimum line sizes.

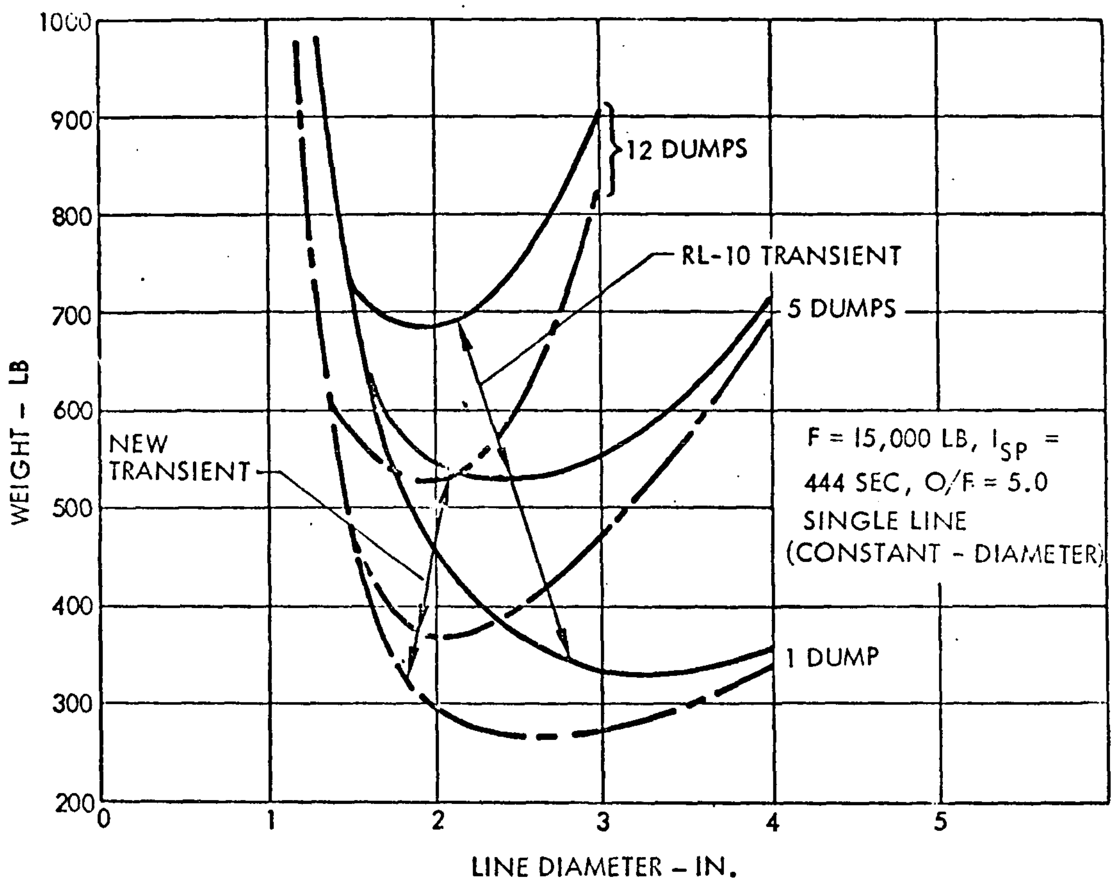
Single Tanks - In Aft Locations. The first set of comparisons, presented in Figs. 9.1-24, 9.1-25, 9.1-26, and 9.1-27, are for single tanks located in the aft regions of the vehicle.

The liquid-oxygen data presented in Figs. 9.1-24 and 9.1-25 compare pump at-the-engine (RL-10) and pump at-the-tank. Conclusions that can be obtained from these sensitivities are:

- Substantial weight savings can result from a less severe engine-start transient than that of the RL-10.
- If the oxygen in the lines can be saved between engine operations, by recovery or cooling, significant weight savings can result.
- Location of the pump at the tank can result in much smaller optimum line sizes.

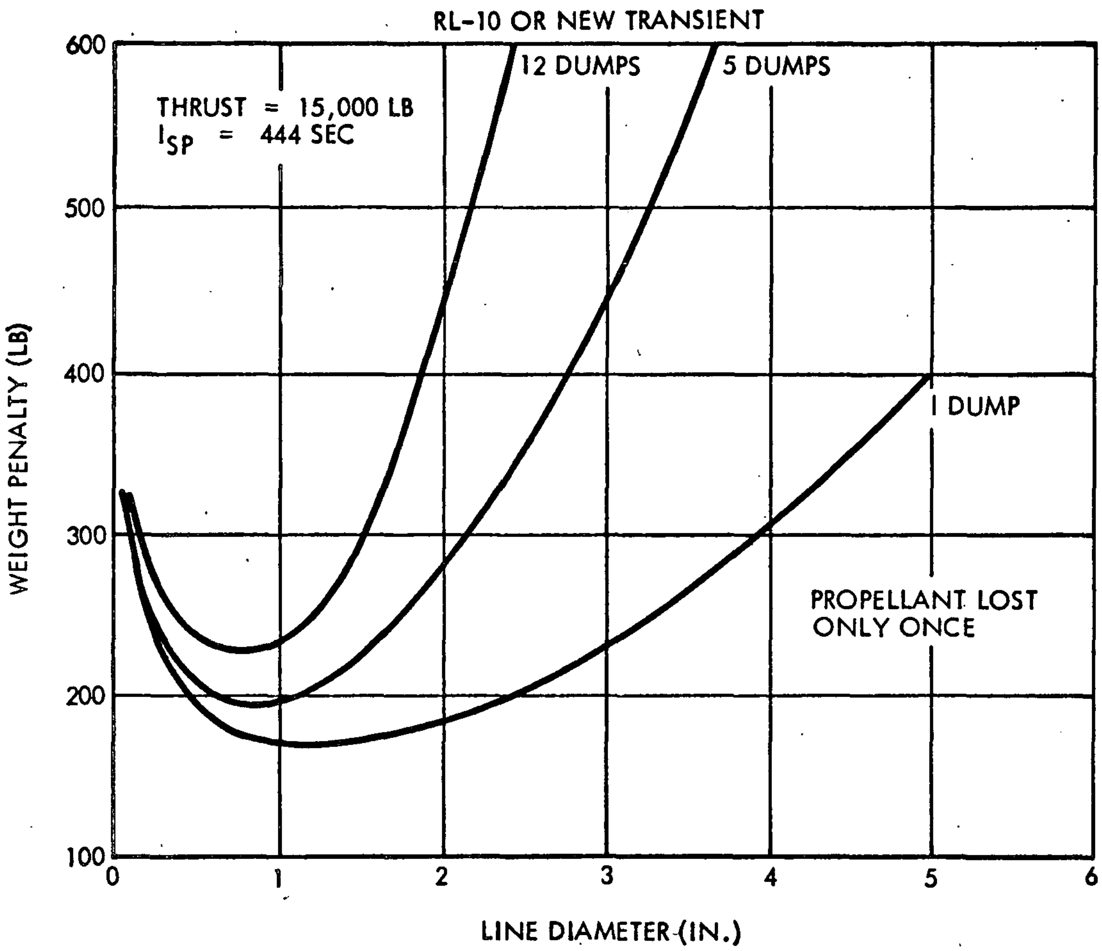
The liquid-hydrogen data presented in Figs. 9.1-26 and 9.1-27, result in much less sensitivity to the transients and propellant losses. Line diameters for pump at-the-tank are smaller.

Single Tanks - In Forward Locations. Data presented in Figs. 9.1-28 and 9.1-29 indicate the same general trends as for tanks in the aft locations, with substantially greater effects on weights, as would be expected. One interesting factor is that the optimum line sizes for the tanks in the forward locations were not very different from the optimum line sizes for the tanks in the aft locations.



D02655(1)

Fig. 9.1-24 Sensitivities of Line Size, Start Transient, and Line Recovery – LO_2 In Aft Tanks (Pump-At-Engine)



D02960(1)

Fig. 9.1-25 Sensitivities of Line Size And Propellant Recovery – LO_2 In Aft Tanks (Pump-At-Tank)

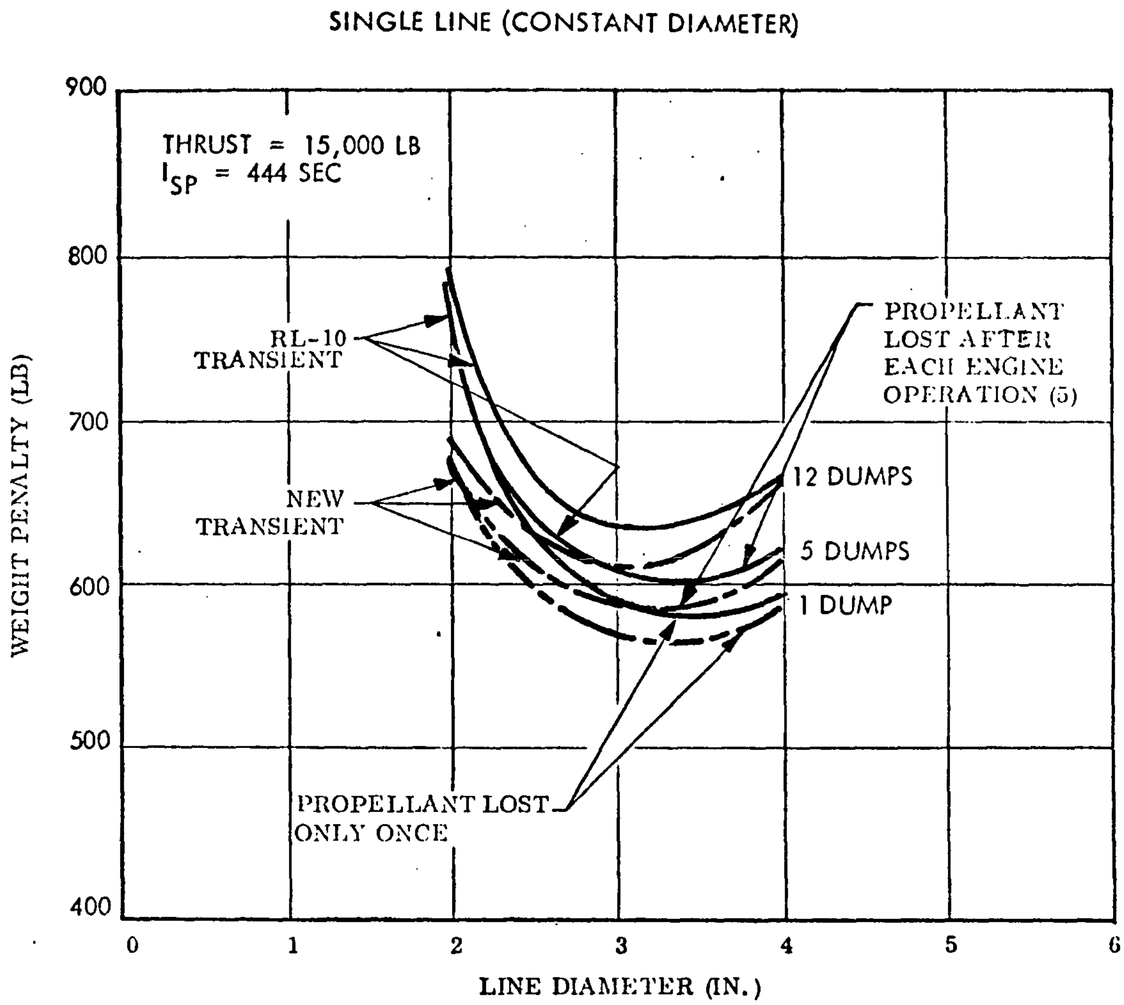
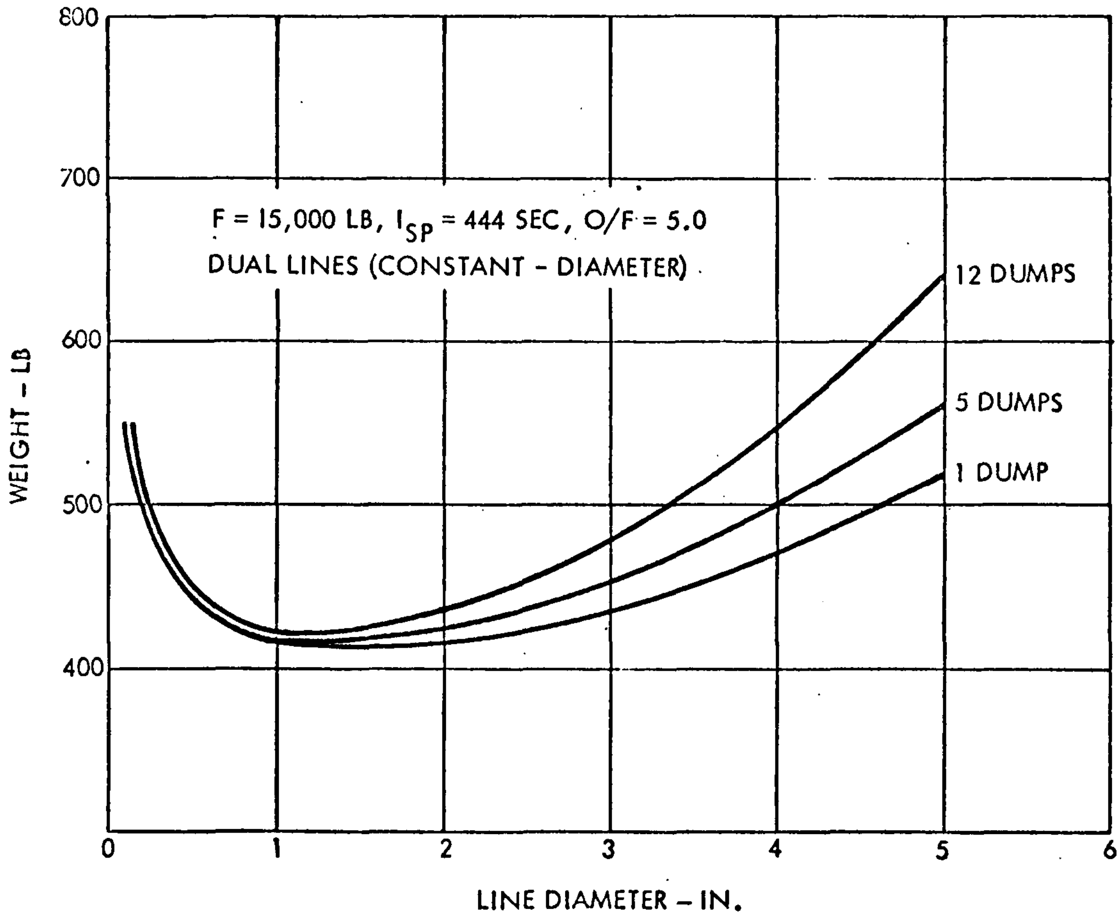
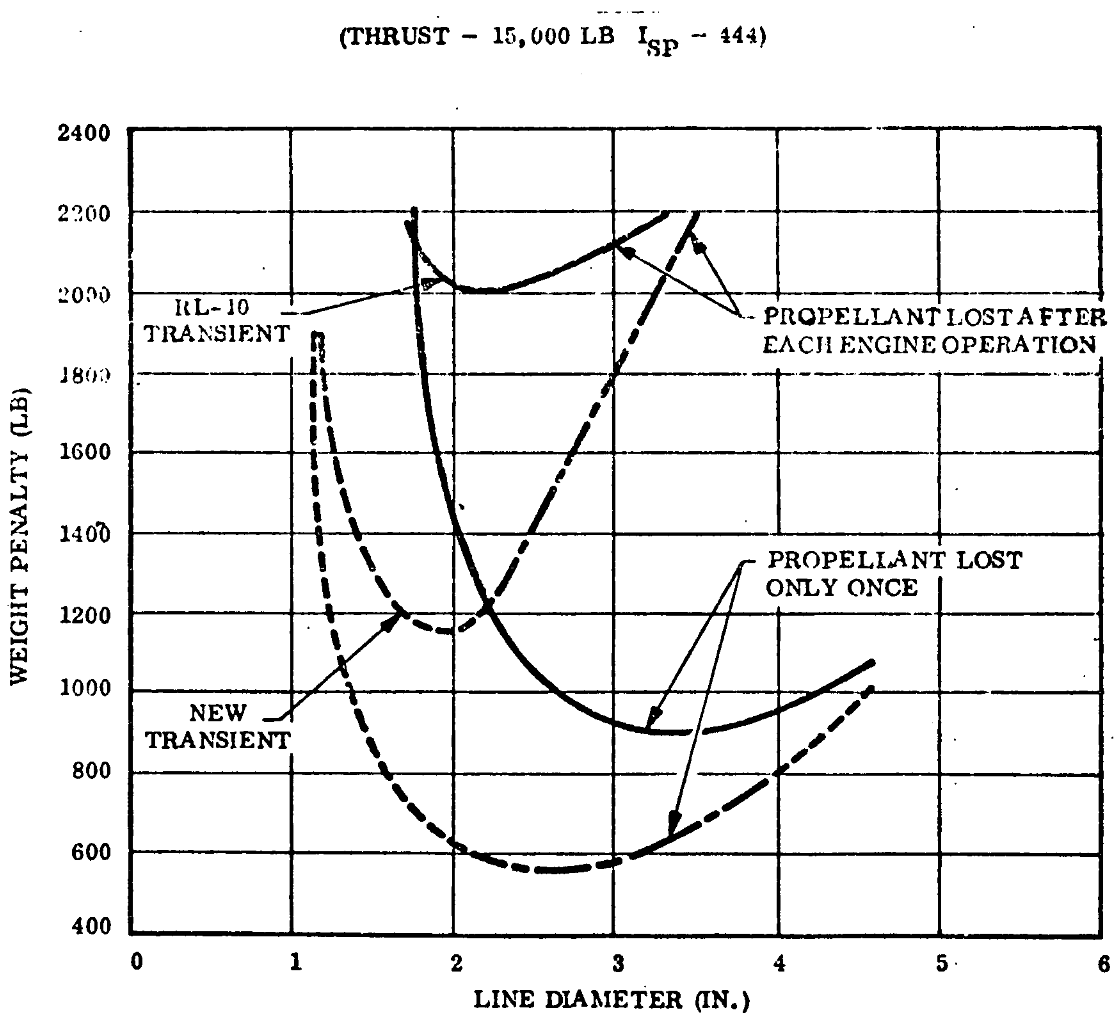


Fig. 9.1-26 Sensitivities of Line Size, Start Transient, and Line Recovery – LH_2 in Aft Tanks (Pump-At-Engine)



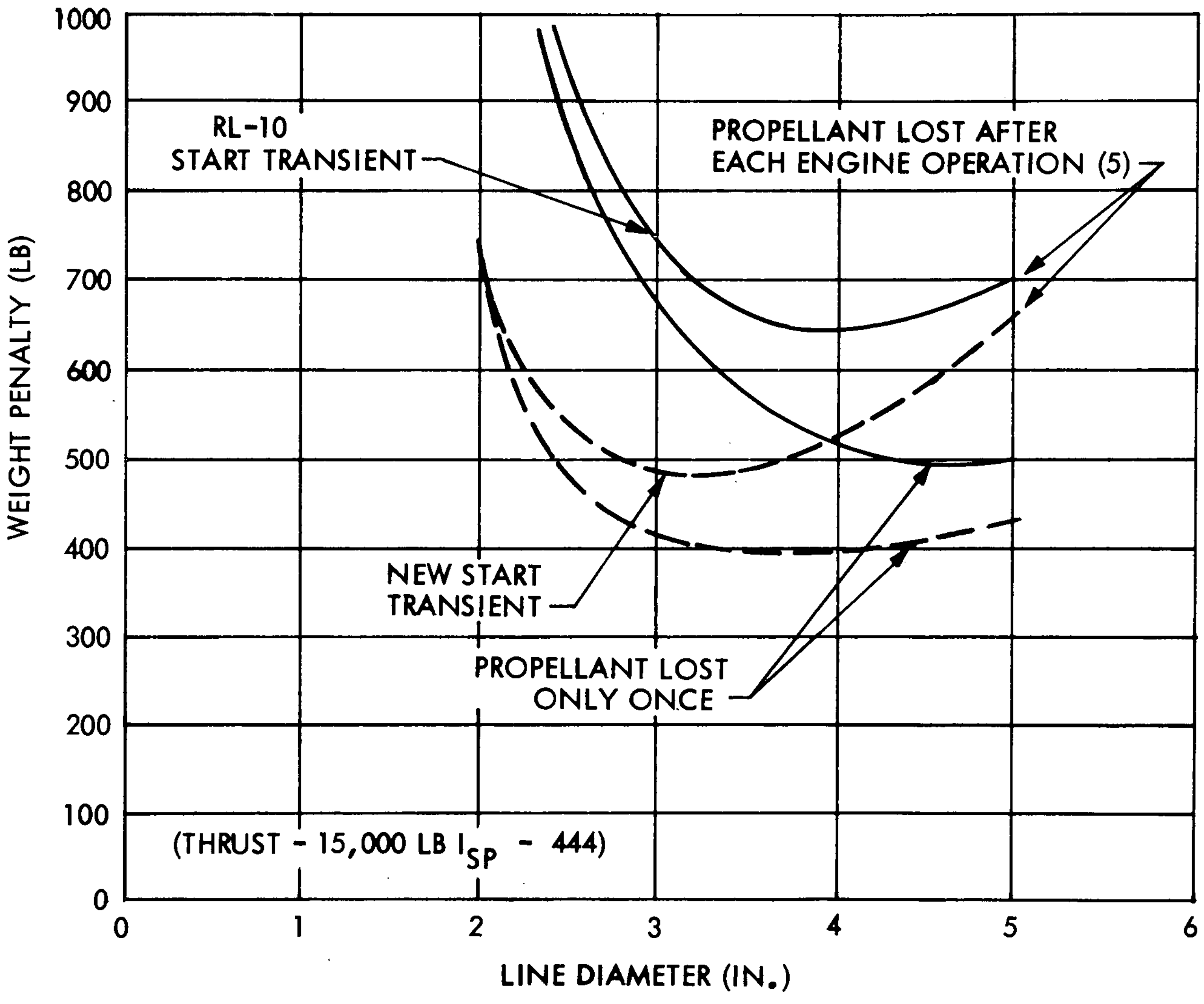
D02961(1)

Fig. 9.1-27 Sensitivities of Line Size And Propellant Recovery – LH_2 In Aft Tanks (Pump-At-Tank)



D02648

Fig. 9.1-28 Sensitivities Of Line Size Start Transient, And Line Recovery - LO_2 In Forward Tanks



D02650

Fig. 9.1-29 Sensitivities Of Line Size, Start Transient, And Line Recovery LH_2 In Forward Tanks

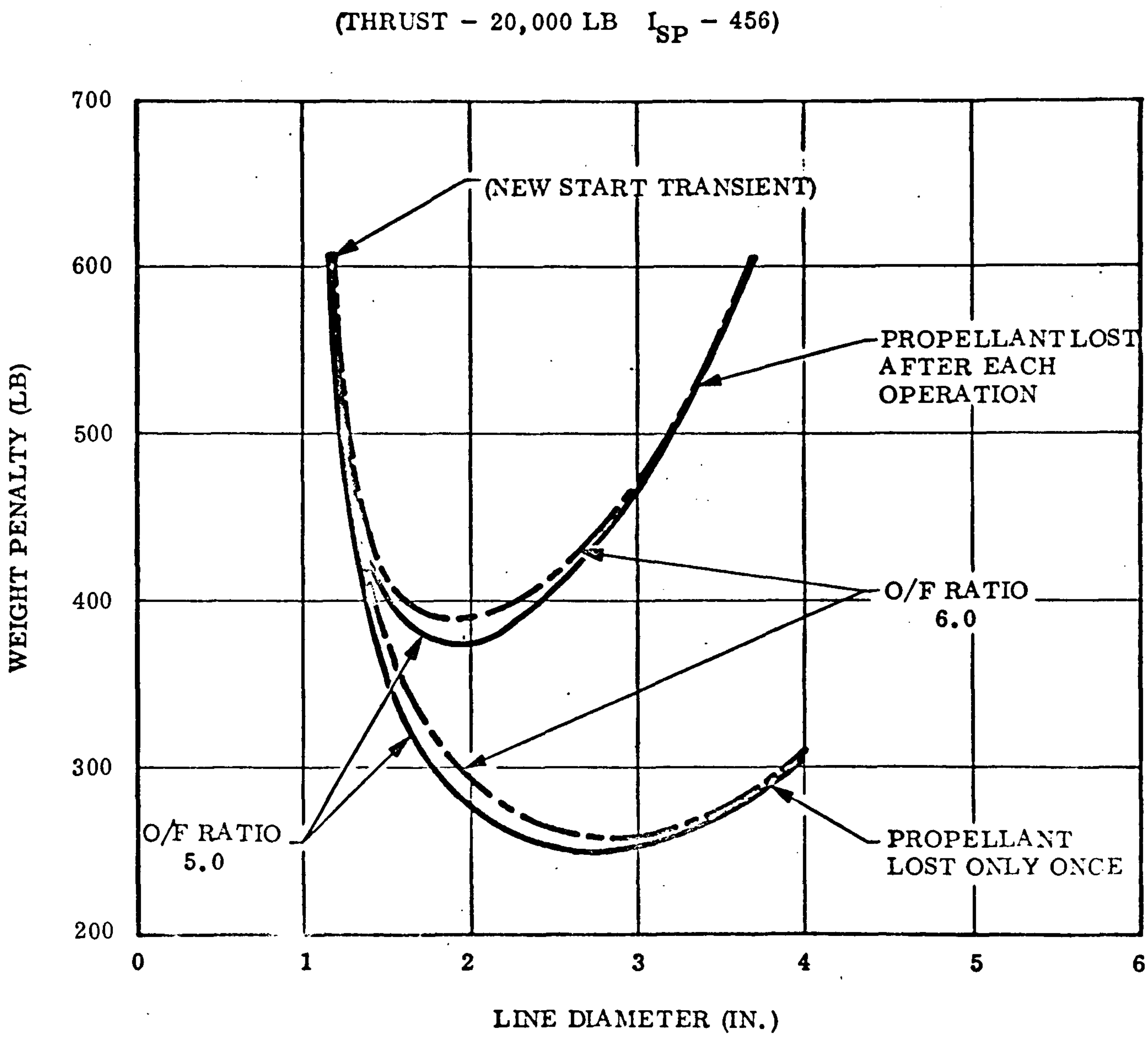
Sensitivity to O/F Ratio. The factors under consideration were examined for sensitivity to O/F ratio, as shown in Fig. 9.1-30. As noted, the O/F ratios produced very little effect.

Dual Tanks. The dual tanks were examined only for pump at-the-engine. This tank arrangement allows not only variations in the feedline but also variations of the lines from individual tanks. Results of the analyses are presented in Figs. 9.1-31 and 9.1-32. As would be expected, the lines from the individual tanks are smaller, with a larger combined feedline than for single tanks.

The weights of the factors under consideration are only slightly higher than for the single tanks.

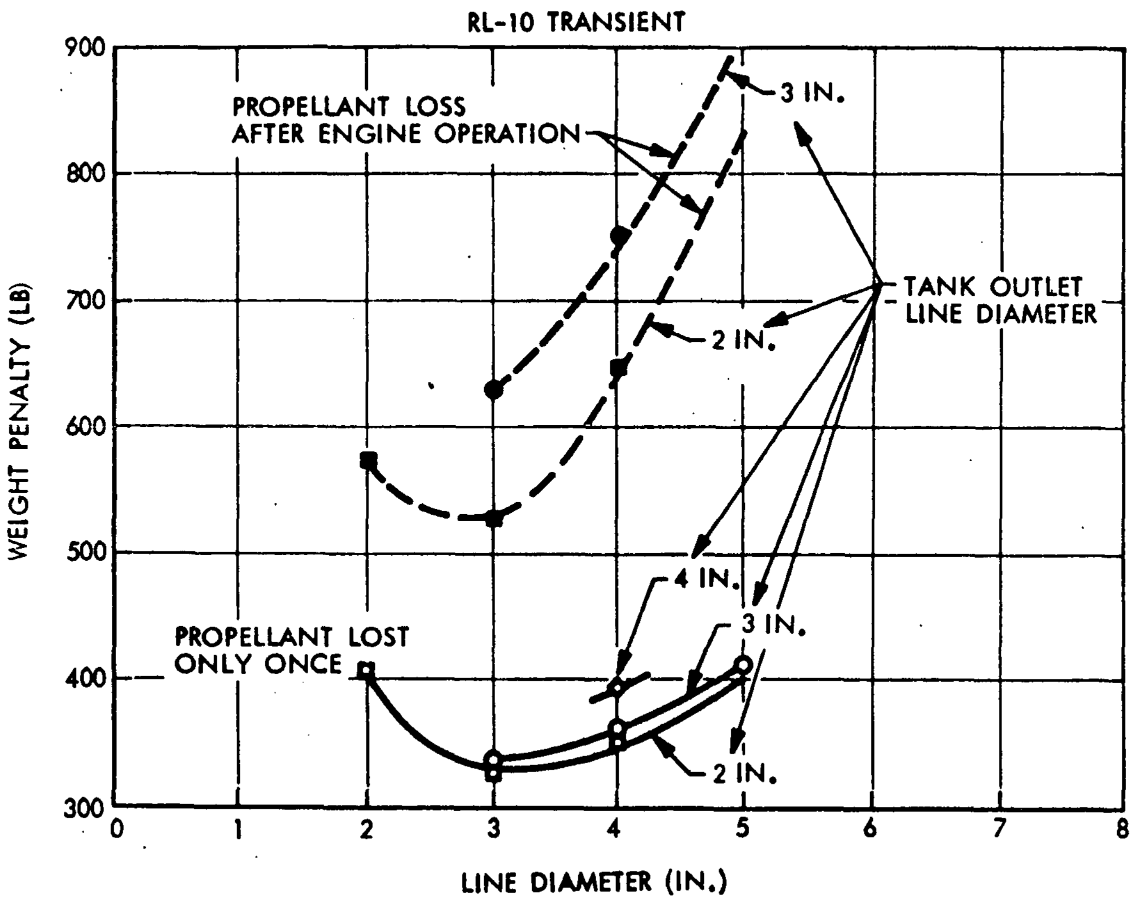
Cascaded Propellant Tanks. Cascaded propellant tanks were considered where the tanks are located side-by-side. All of the tradeoff factors previously presented were included in the evaluations. The tank interconnect line becomes a variable in the analyses. Results of the examinations are presented in Figs. 9.1-33 and 9.1-34. The pressure drop and residuals resulting from this interconnect line in side-by-side tanks has a significant impact on the results. A means of draining this line would reduce residuals.

OMPS with Start Tanks. This study examined an OMPS, which was not part of an integrated system, but employed a start tank that is considerably smaller than that used in integrated systems. This concept used helium to pressurize the start tank, which was sized to contain sufficient propellant to cool down the RL-10 engine and for operating the engine during the startup transient and at steady-state for a sufficient time to settle the propellant in the main storage tank. After the main storage tank propellants are settled and the main tank is pressurized by bleed gas from the engine, the tank interconnect valve is opened, allowing the propellant to flow from the main tank to the start tank and then to the engines. Initially, the flow from the main tank is greater than that required by the engine, thus refilling the start tank. After the start tank is refilled, the pressures are such that the flow from the main tank just equals that which is required by the engine.



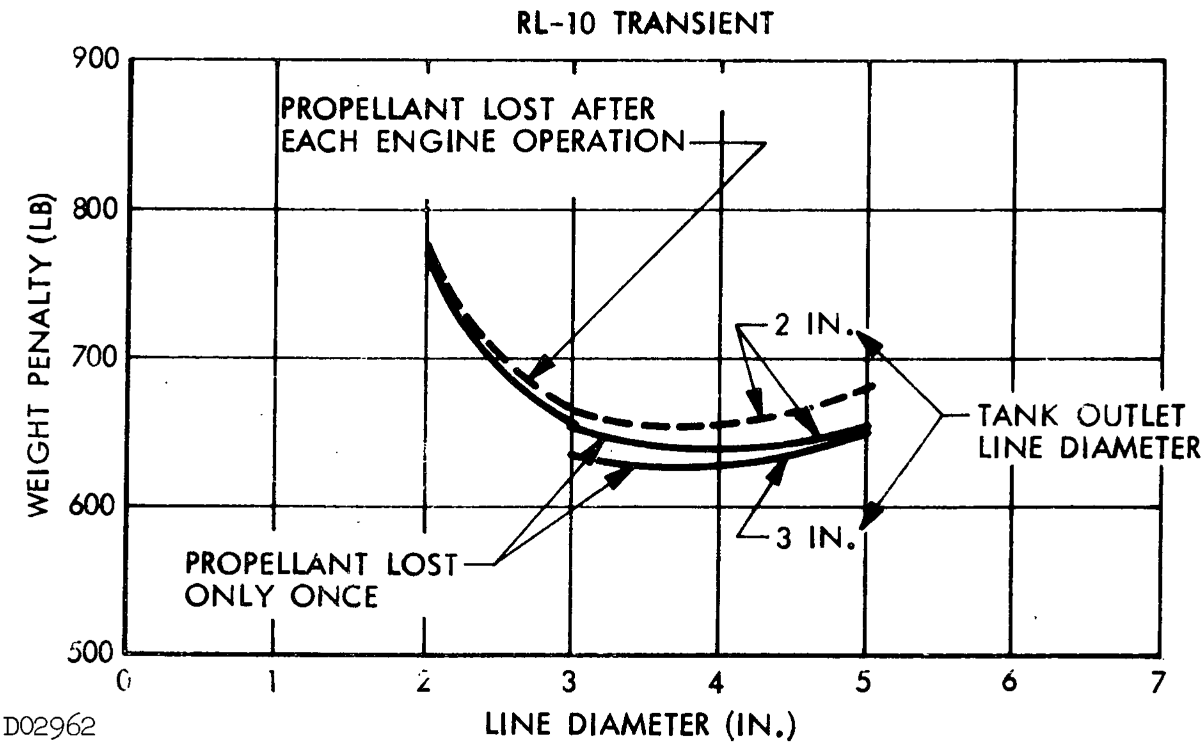
D02660

Fig. 9.1-30 Sensitivity To O/F Ratio - LO_2 In Aft Tanks



D02977

Fig. 9.1-31 Sensitivities To Line Size And Propellant Recovery LO_2 In Dual Tank (Pump-At-Engine)



D02962

Fig. 9.1-32 Sensitivities To Line Size And Propellant Recovery LH_2 In Dual Tanks (Pump-At-Engine)

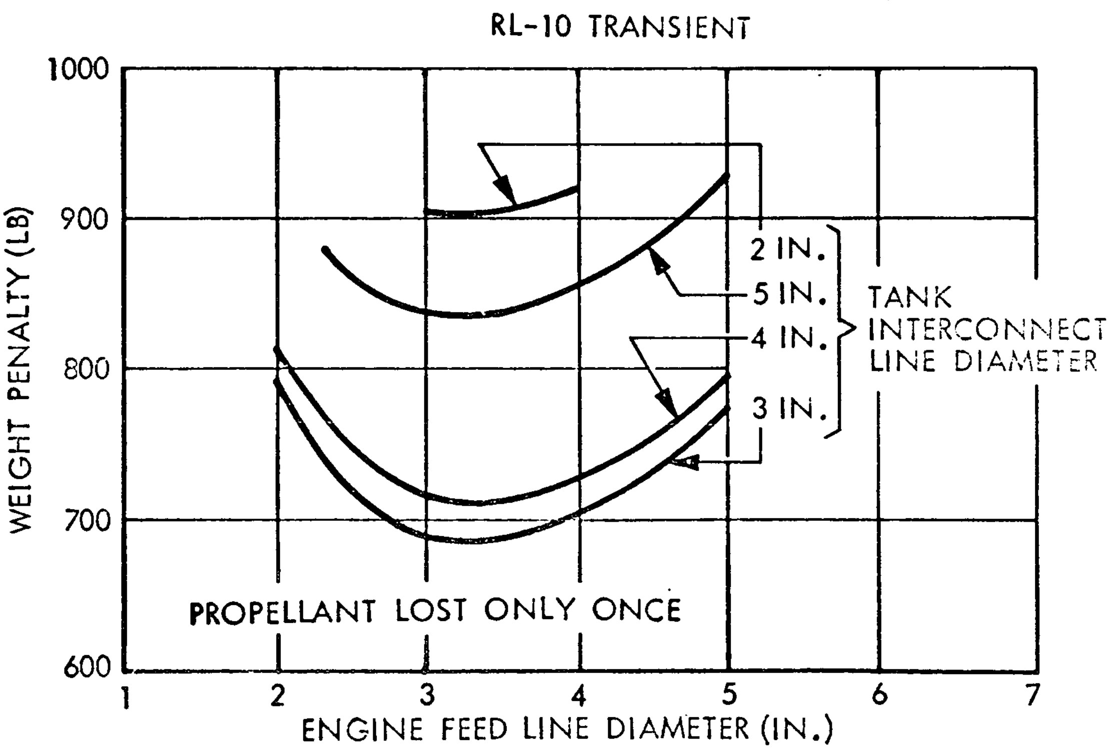
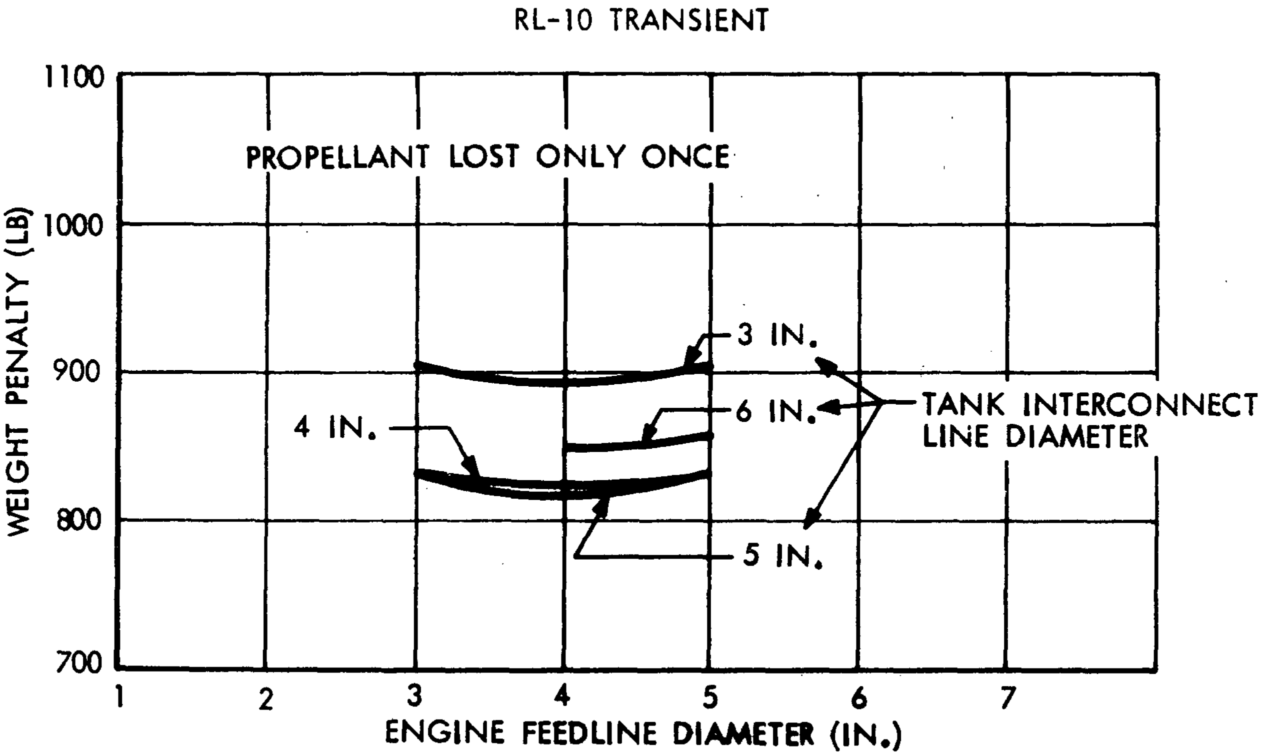


Fig. 9.1-33 Cascaded LO_2 Tanks (Side-By-Side) – Sensitivity To Line Sizes



D02966

Fig. 9.1-34 Sensitivities To Line Sizes – Cascaded LH_2 Tanks (Side-By-Side)

Figure 9.1-35 shows a typical pressure history for the main tank and start tank during the start and refill cycle. The start tank is sized so that the pressure at its depletion equals the steady-state flow pressure in the line, and the pressure at the end of the start transient is equal to the minimum required pressure drop to accelerate the propellant during the startup transient.

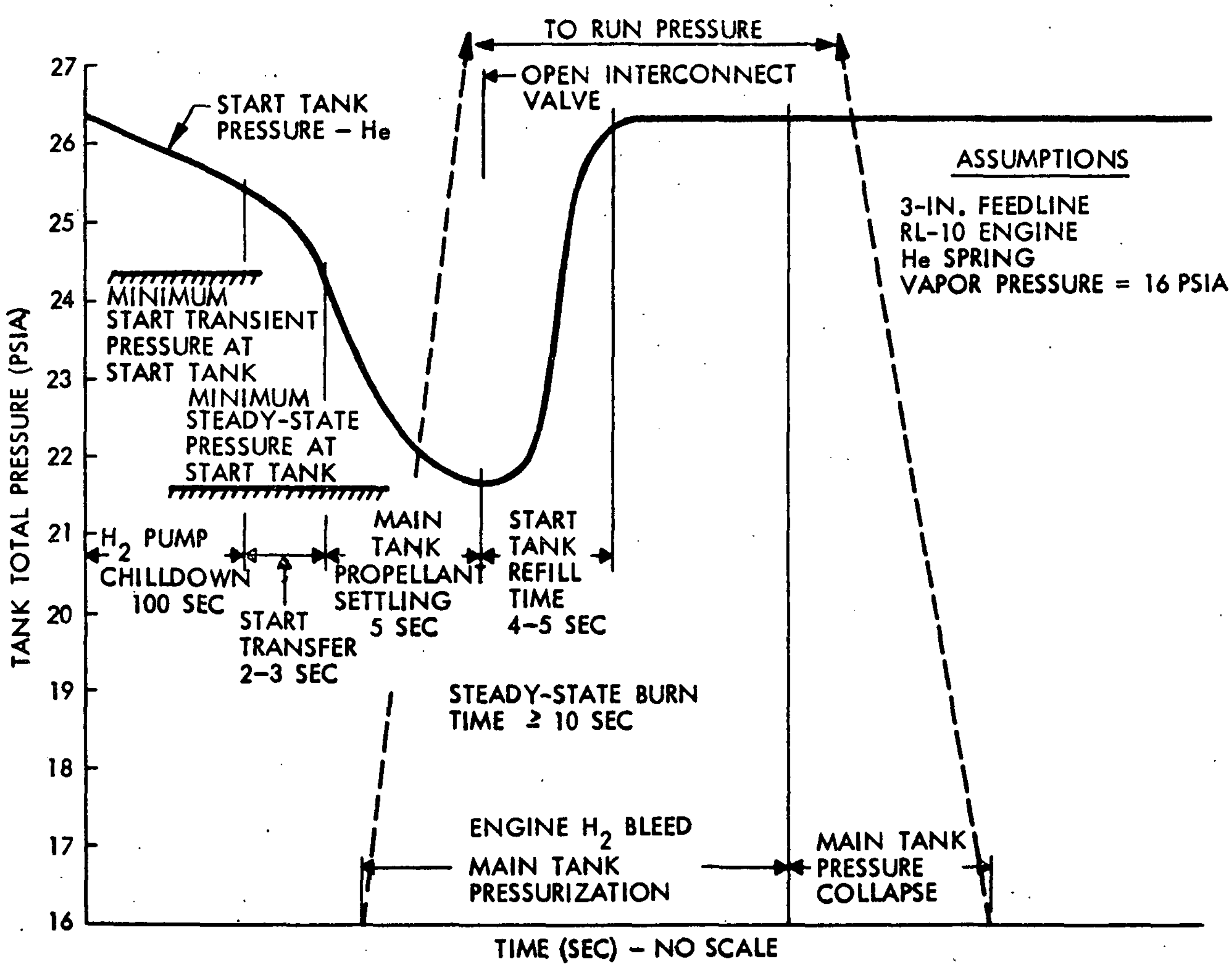
Figures 9.1-36 and 9.1-37 show the effect of line size on the system weight for O_2 and H_2. The weight includes the following items:

- Main storage tank
- Start tank
- Helium pressurant
- Propellant feed lines
- Propellant components
- Propellant trapped in the lines, which is dumped once (at the end of the mission)

The use of a start tank in a nonintegrated OMPS tank results in a weight and complexity which makes it undesirable.

Comments Regarding Sensitivities of Line Sizes, Start Transients, and Feedline Propellant Recovery. A comparison of the overall configurations, compared for RL-10 transient only, is presented in Figs. 9.1-38 through 9.1-41. As indicated, there is little difference between the single and dual tanks, and the cascade tank arrangement is heavier for the parameters under consideration. From data presented in these figures and in the previous conclusions, the following general conclusions are formulated:

- The location of the pump at-the-tank results in lower line sizes and lighter weights.
- The location of the pump at-the-tank lowers the sensitivity to the pump-start transient.



D02954

Fig. 9.1-35 Start Tank Configuration – LH_2 Tank (Assumed Operational Sequence)

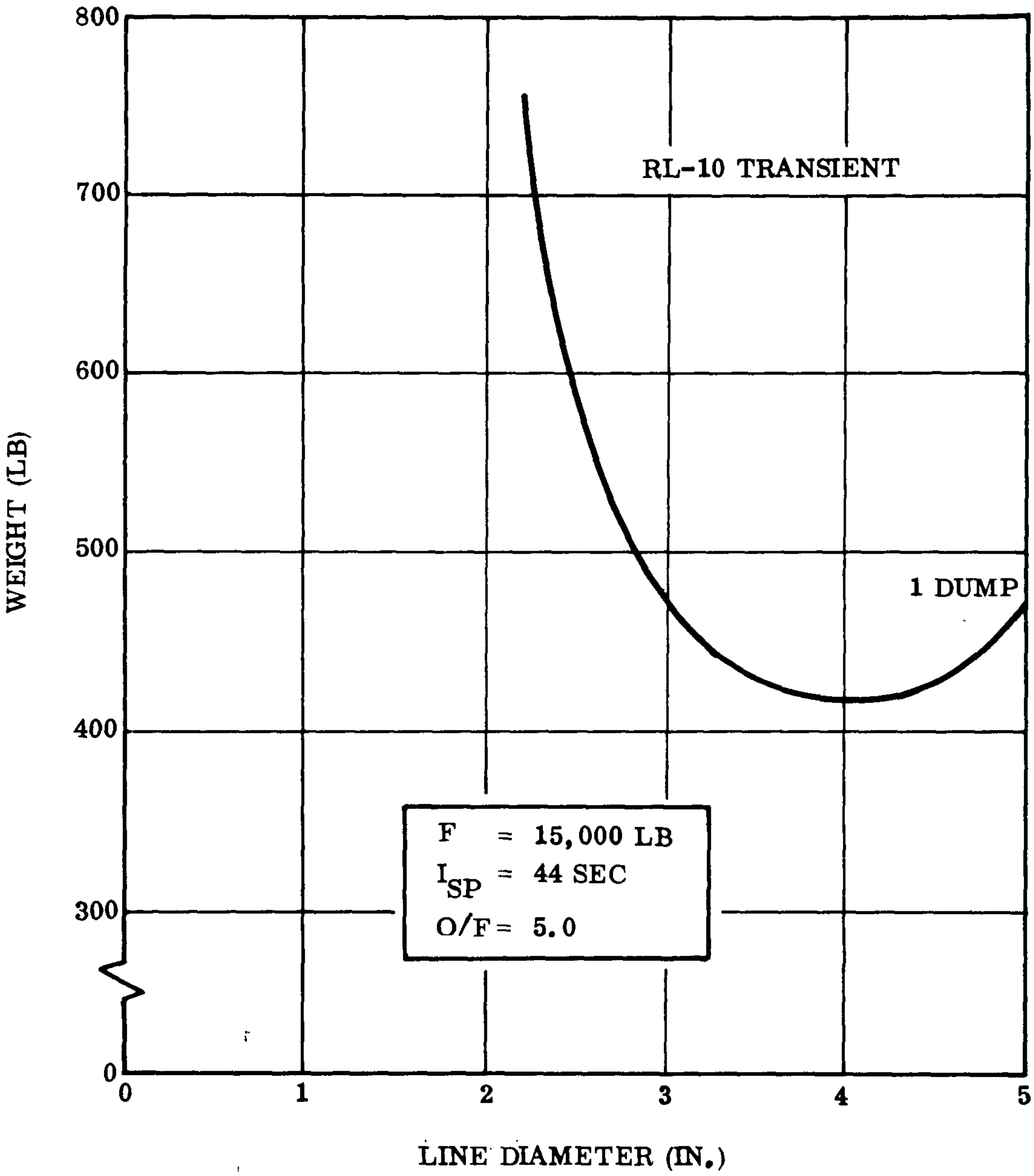


Fig. 9.1-36 Start Tank Configuration – LO_2 Tank (Pump-At-Engine)

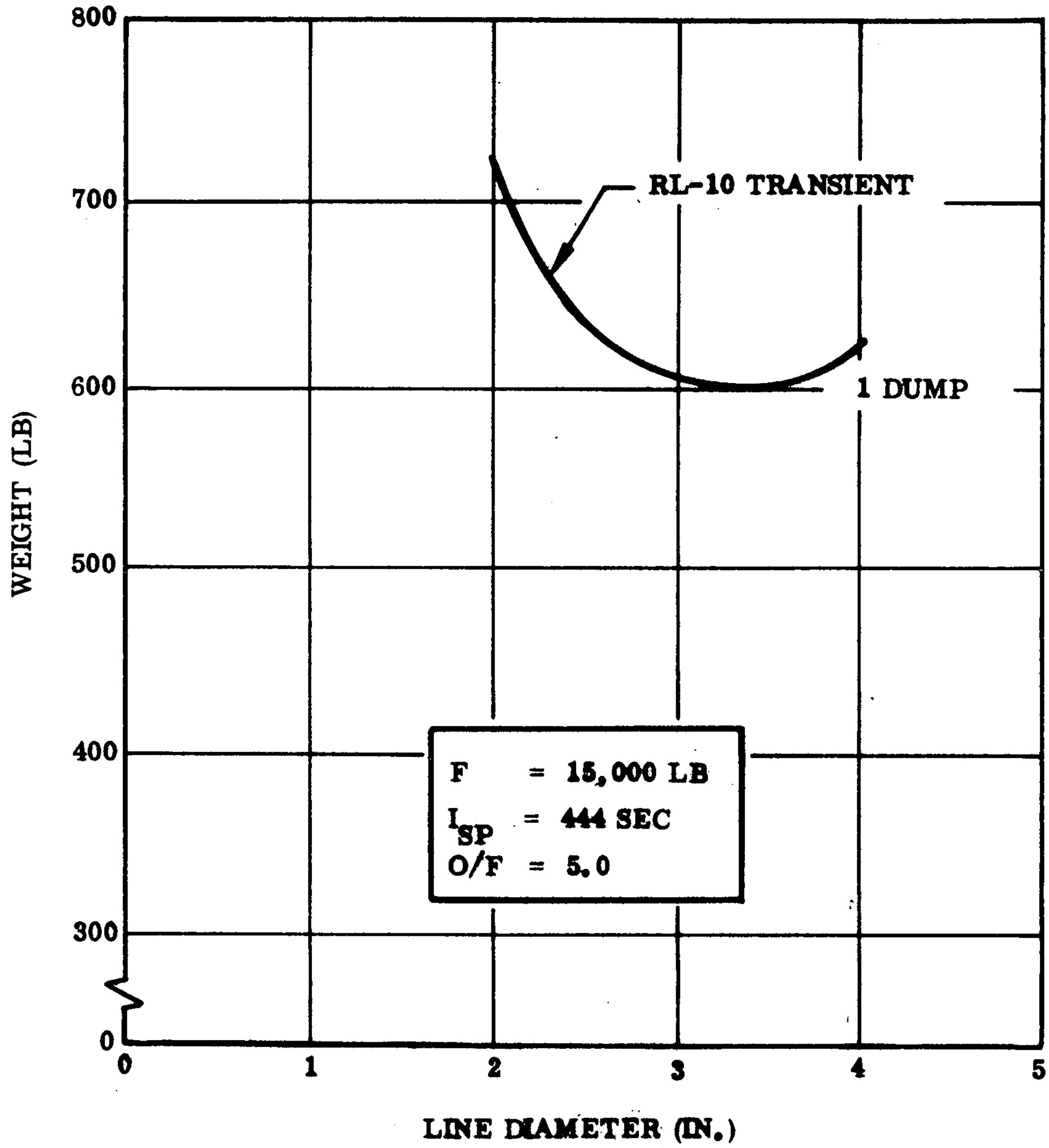
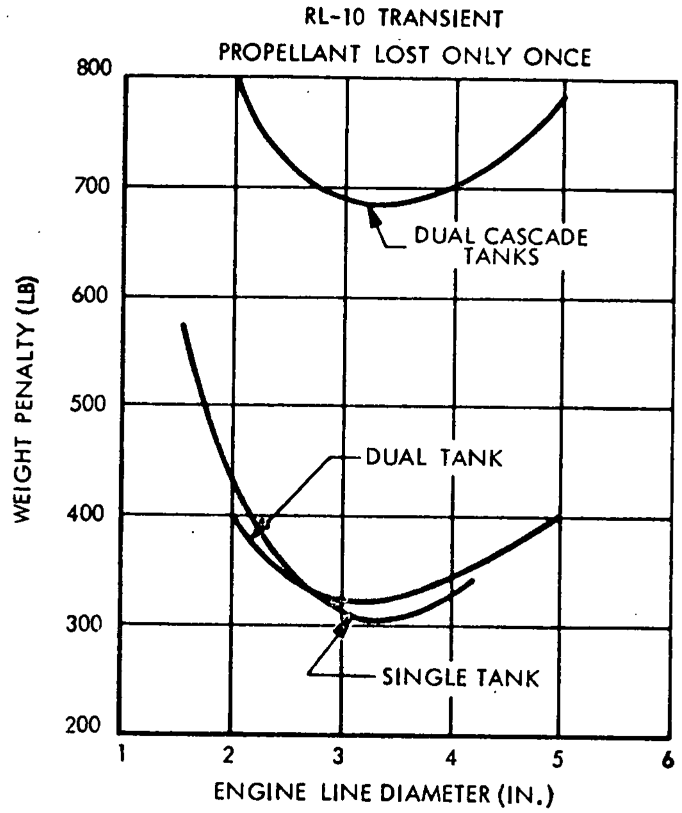
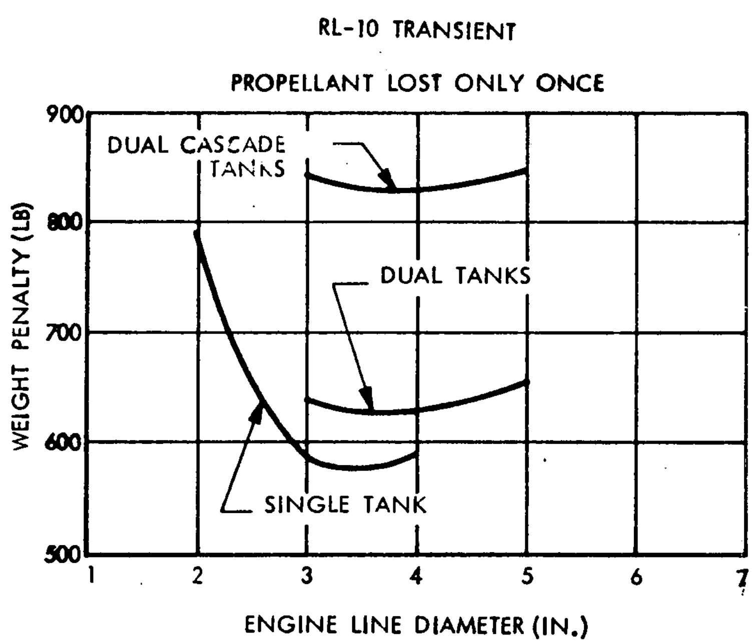


Fig. 9.1-37 Start Tank Configuration — LH_2 Tank (Pump-At-Engine)



D02965

Fig. 9.1-38 Comparisons of Sensitivities To Line Sizes – OMPS Configurations LO_2 Tanks



D02963

Fig. 9.1-39 Comparisons Of Sensitivities To Line Sizes – OMPS Configurations LH_2 Tanks

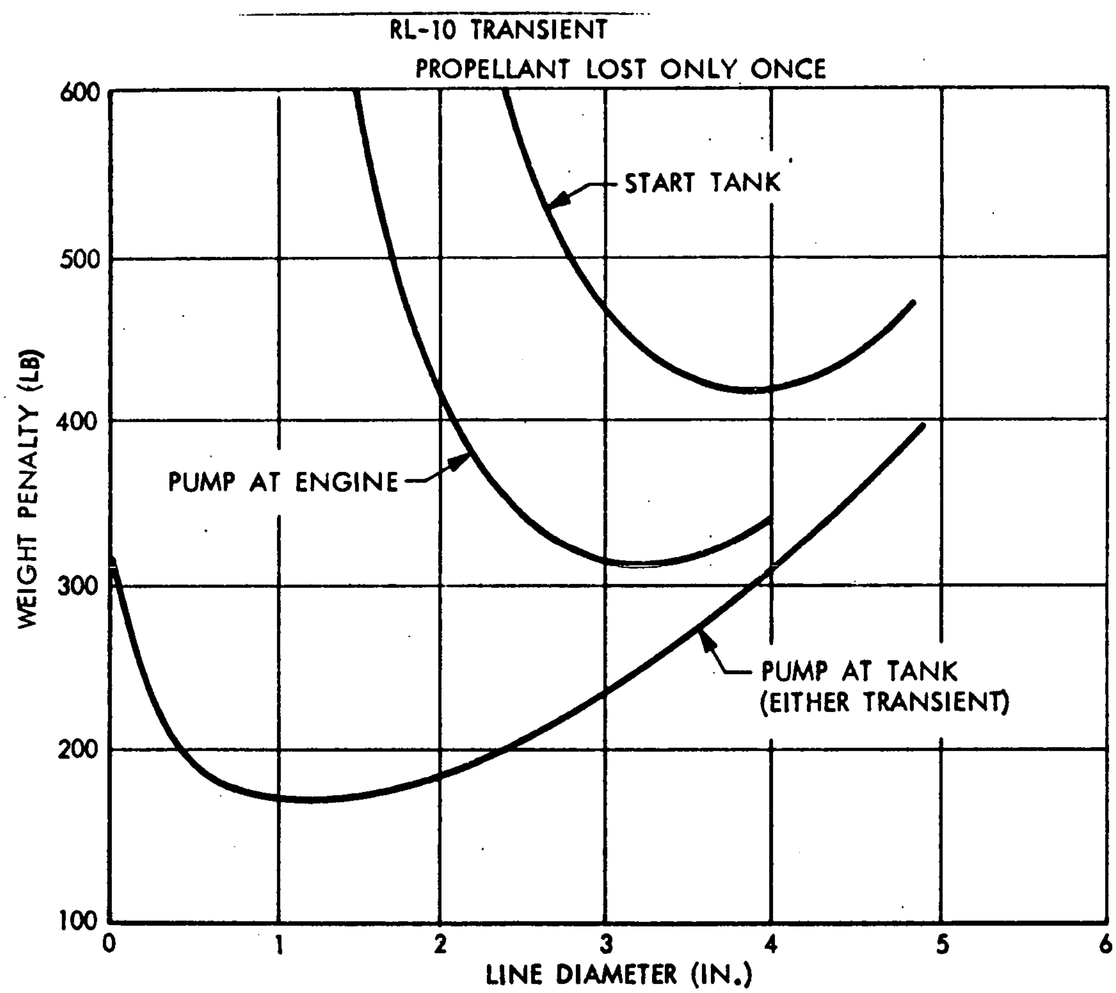


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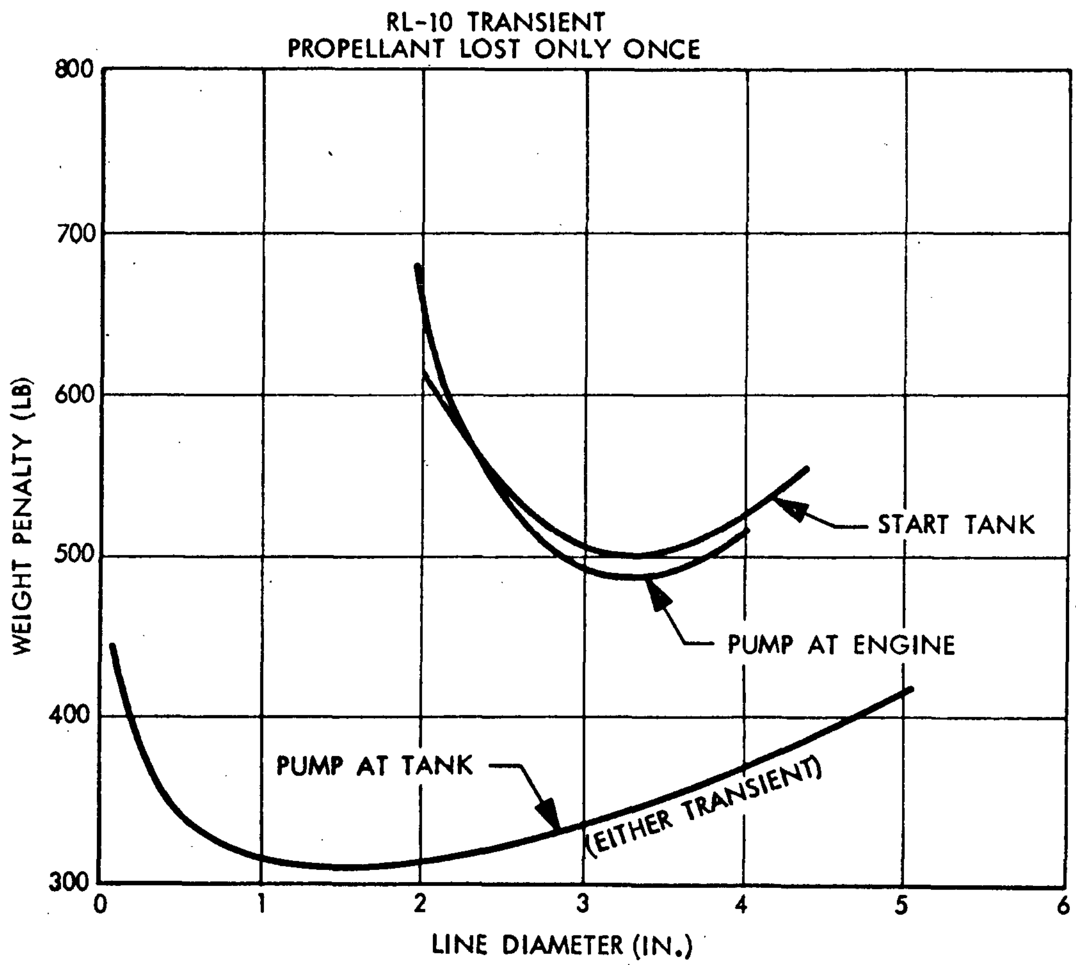
Fig. 9.1-40 Comparison Of Sensitivities To Line Sizes – OMPS LO_2 Single Tank Configuration



D02947

Fig. 9.1-41 Comparison Of Sensitivities To Line Sizes – OMPS LH_2 Single Tank Configuration

- The start tank in nonintegrated systems results in some weight penalties with no other apparent advantages.

9.1.3.4 Cascade Tank Analyses. The complexity of the cascade tank systems required extensive analyses. Two tanks, connected in-series, are utilized for each propellant. The lower or downstream tank is completely filled (97 percent), whereas for the nominal mission, the upper or upstream tank is only about half filled. During operation, it is desired to drain the upstream tank as soon as possible and then isolate this tank from the system. An analysis was made to determine the required pressure differences in the tanks and transfer-line size, so that the upstream tank will be depleted quickly.

During the system startup procedure, the upstream tank is isolated from the system. The lower tank is pressurized to the start-transient requirements, and propellant is withdrawn to chilldown the engine, start up the engine, and supply the engine for a period sufficient to settle the propellant in the upper tank. When the upper tank propellant is settled, the transfer line valves are opened to allow flow from the upper tank. Upper tank pressurization is provided by engine bleed vapor. The pressure differentials between the tanks and the transfer-line size must be great enough to supply a flow rate sufficient (1) to supply the engine at steady-state and (2) to replenish the propellant in the lower tank that was used in the startup procedure. The effect of transfer-line size and initial pressure differential between the propellant tanks (on the net amount of propellant transferred and the time required to transfer this propellant) is shown in Figs. 9.1-42 through 9.1-45.

The optimization of the O_2 transfer line and the upper tank-insulation thickness is shown in Fig. 9.1-46. These two parameters have a direct effect on the following:

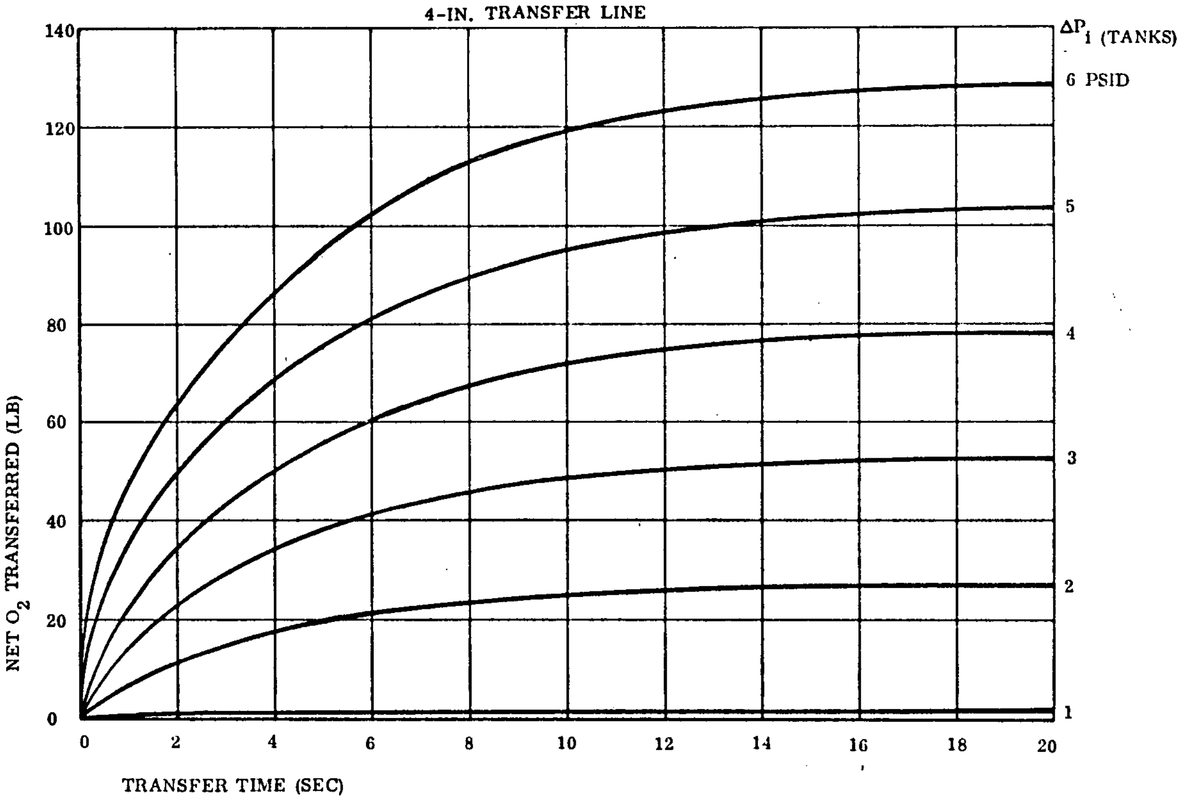


Fig. 9.1-42 Effect of Initial Tank Differential Pressure and Transfer Time on the Net LO_2 That Can be Transferred

5 IN. TRANSFER LINE

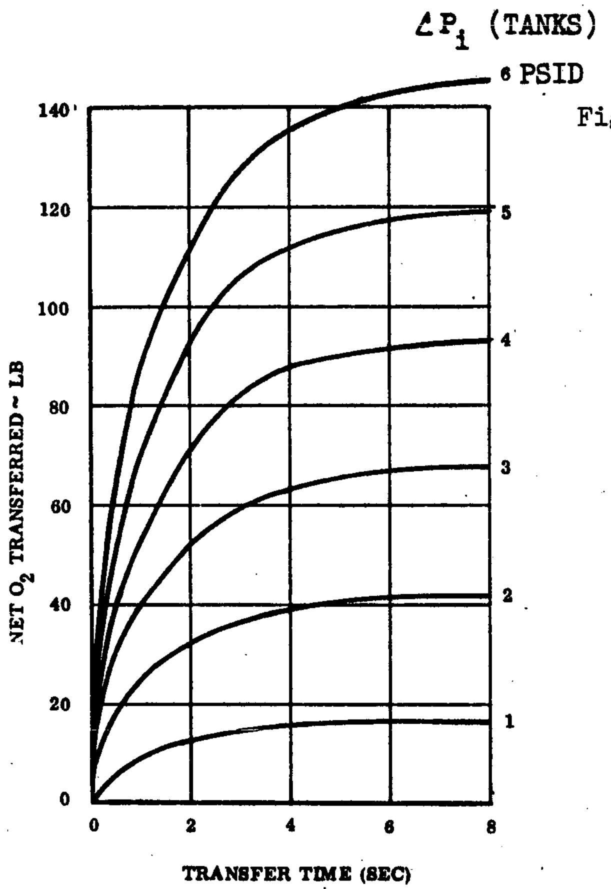


Fig. 9.1-43 Effect of Initial Tank Differential Pressure and Transfer Time on Net LO_2 That Can Be Transfered

6 IN. TRANSFER LINE

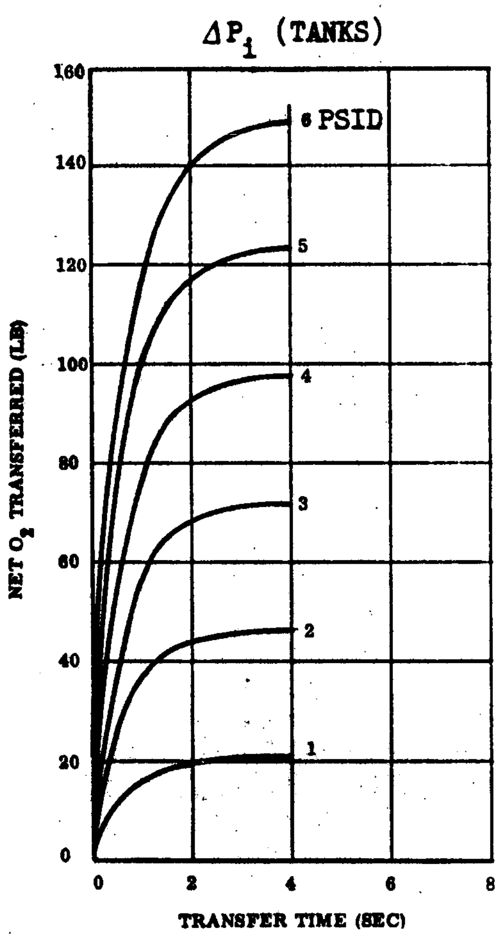


Fig. 9.1-44 Effect of Initial Tank Differential Pressure and Transfer Time on Net LO_2 That Can Be Transfered

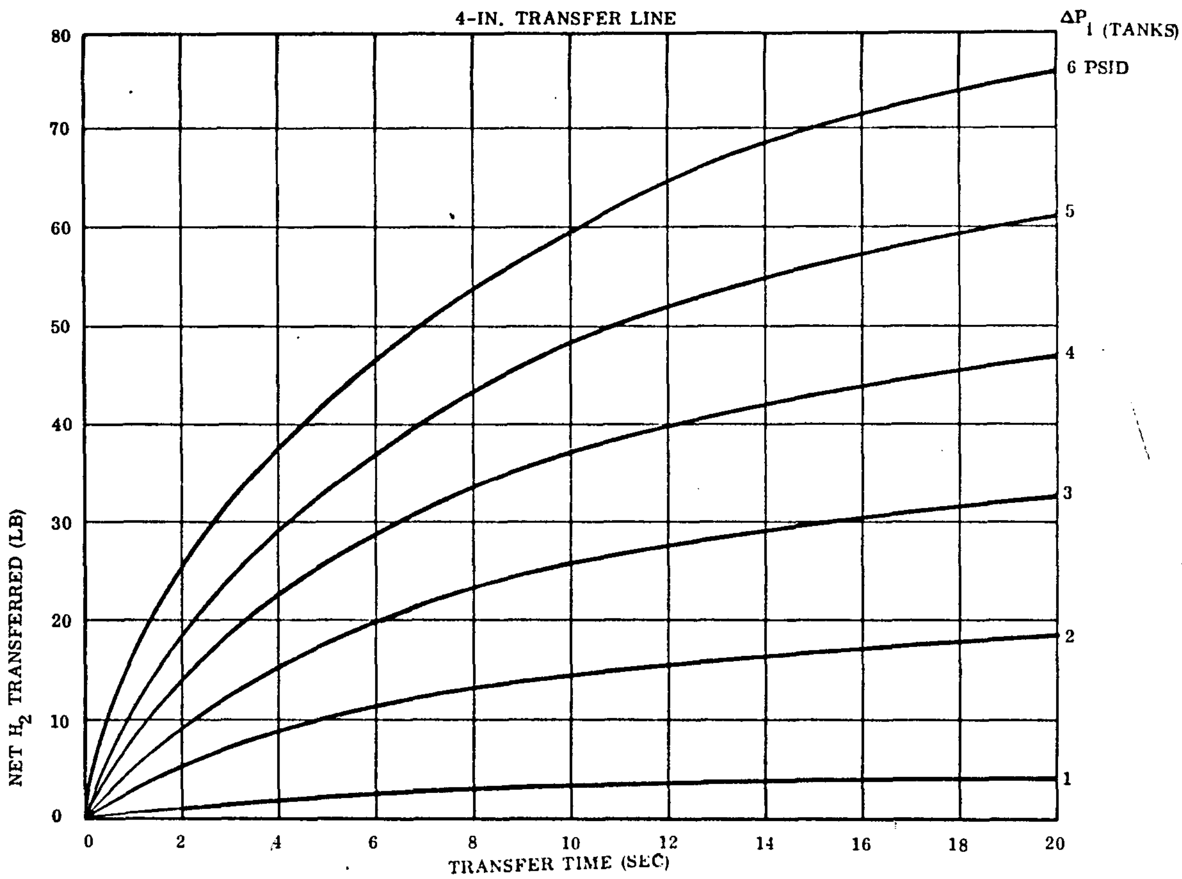
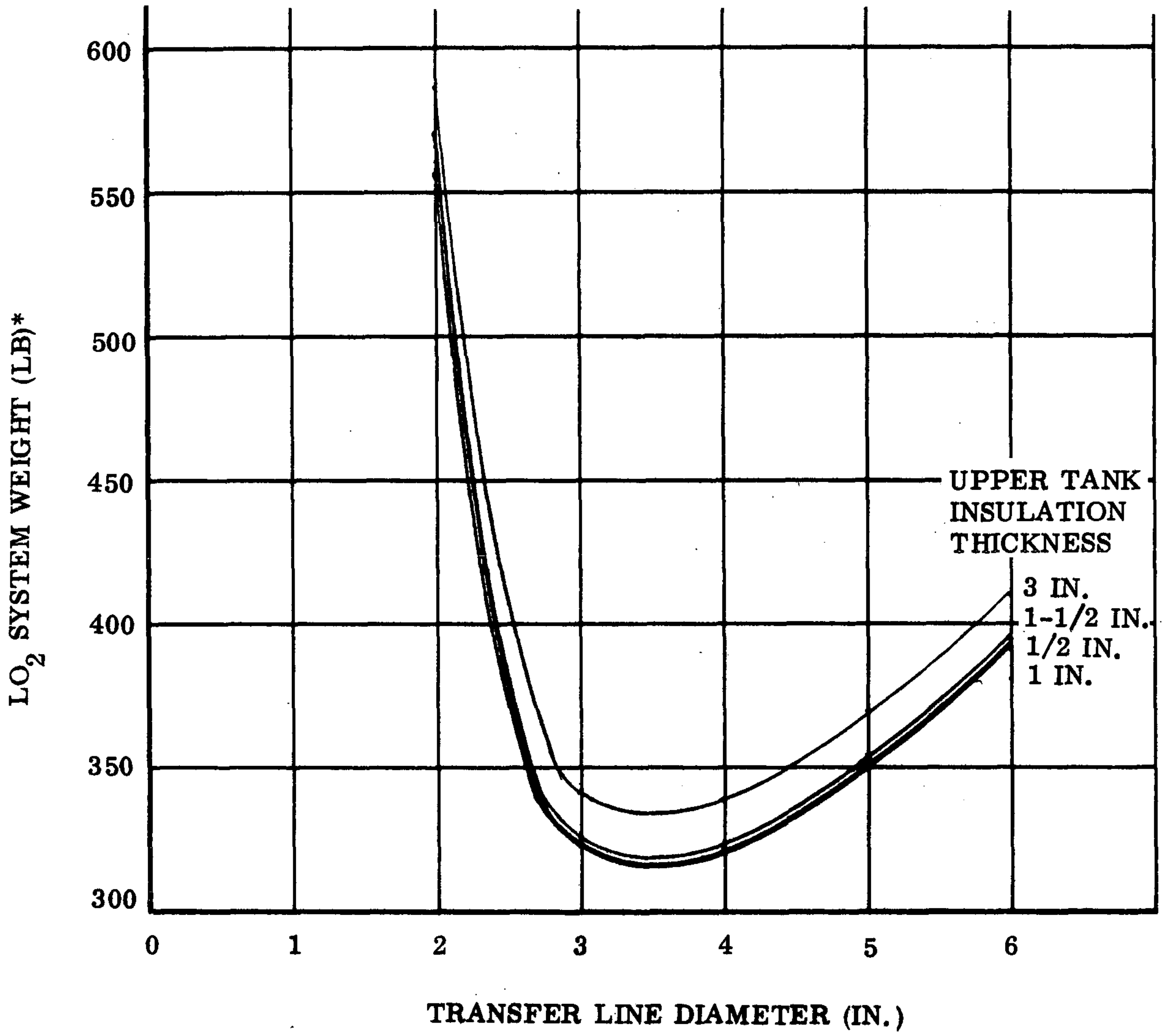


Fig. 9.1-45 Effect of Initial Tank Differential Pressure and Transfer Time on the Net LH_2 That Can be Transferred



*WEIGHT OF TANKAGE TRANSFER LINE AND VALVES/UPPER TANK INSULATION, H_2 TO HEAT ENTERING UPPER TANK, AND O_2 TRAPPED IN TRANSFER LINE STANDPIPE

Fig. 9.1-46 Optimization of LO_2 Transfer Line Size and Upper Tank Insulation Thickness

C

- Tankage weight (tank shells due to required operating pressures)
- Transfer-line valve weights
- Upper tank-insulation weight
- LO_2 trapped in the standpipe portion of the transfer line
- Amount of H_2 required to extract the heat, which enters the lower tank via the liquid and the system through the upper tank insulation and is brought into the upper tank via the engine-bleed vapors.

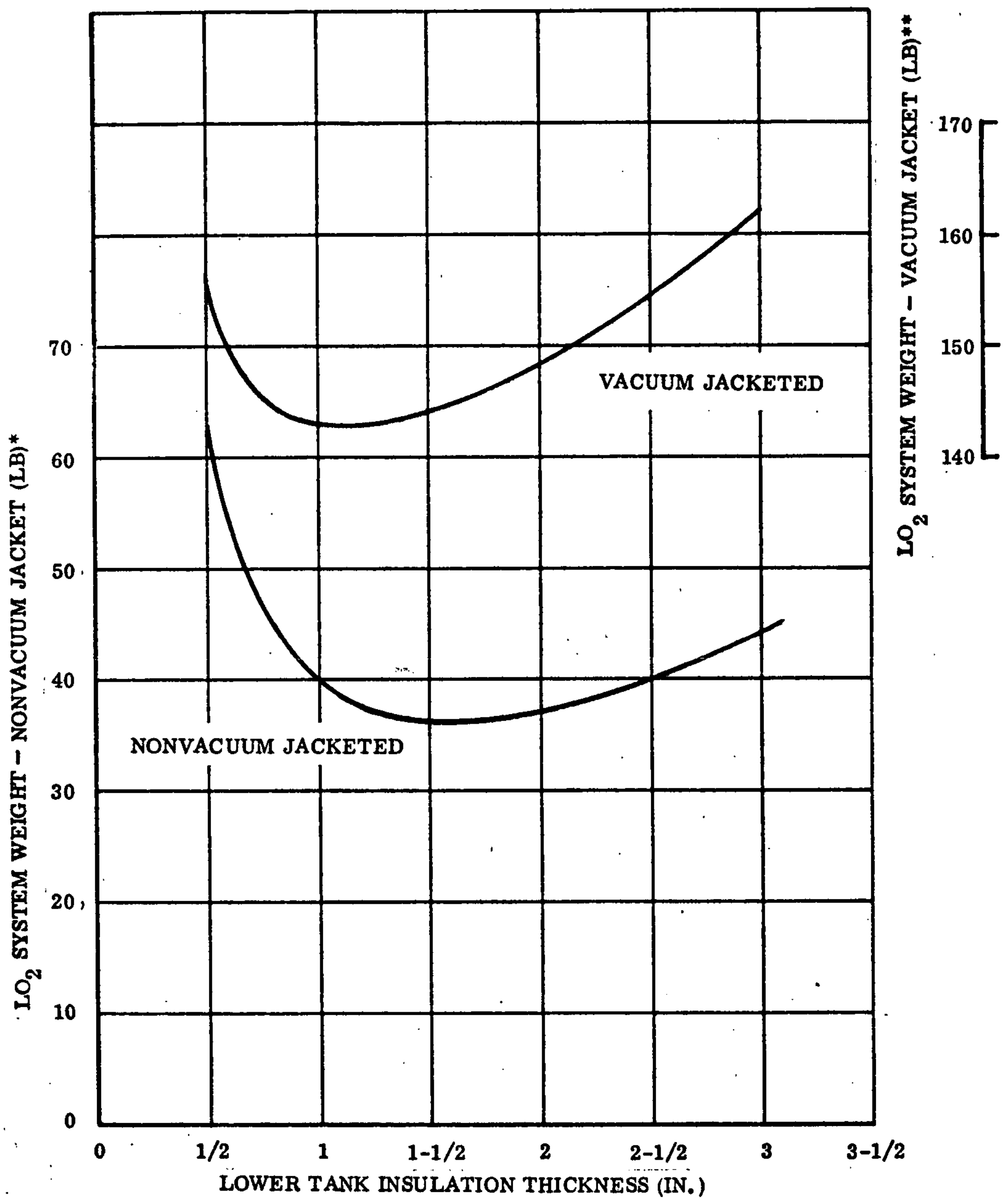
The optimization of the O_2 lower tank-insulation thickness is shown in Fig. 9.1-47 for both the vacuum-jacketed and nonvacuum-jacketed case. Vacuum jackets were considered for the lower tanks only. These parameters have an effect on the insulation weight, the vacuum-jacket weight and the required H_2 to extract the heat, which enters the system through the lower tank insulation.

For Figs. 9.1-46 and 9.1-47, the required H_2 used for cooling was based on the assumption that no H_2 was available from the H_2 tank-cooling system.

Optimization of the H_2 tank-insulation thicknesses and use of vacuum jackets is shown in Fig. 9.1-48. These parameters have an effect on the following:

- Tank shell weights
- Insulation weights (both multilayer insulation on the lower and upper tank and the foam on the upper tank)
- Vacuum-jacket weight
- Vent losses (H_2 required to extract the heat entering the lower tank).

A 4-in. transfer-line diameter was used for this study. Two upper tank-insulation combinations were used. The upper tank-insulation thickness was determined by the criterion that just prior to the last burn, which is supplied by the upper tank (Height Burn), the vapor pressure will have risen



*WEIGHT OF LOWER TANK INSULATION AND H_2 TO EXTRACT HEAT ENTERING LOWER TANK

**WEIGHT OF LOWER TANK INSULATION, VACUUM JACKET, AND H_2 TO EXTRACT HEAT ENTERING LOWER TANK

Fig. 9.1-47 LO_2 System Weight

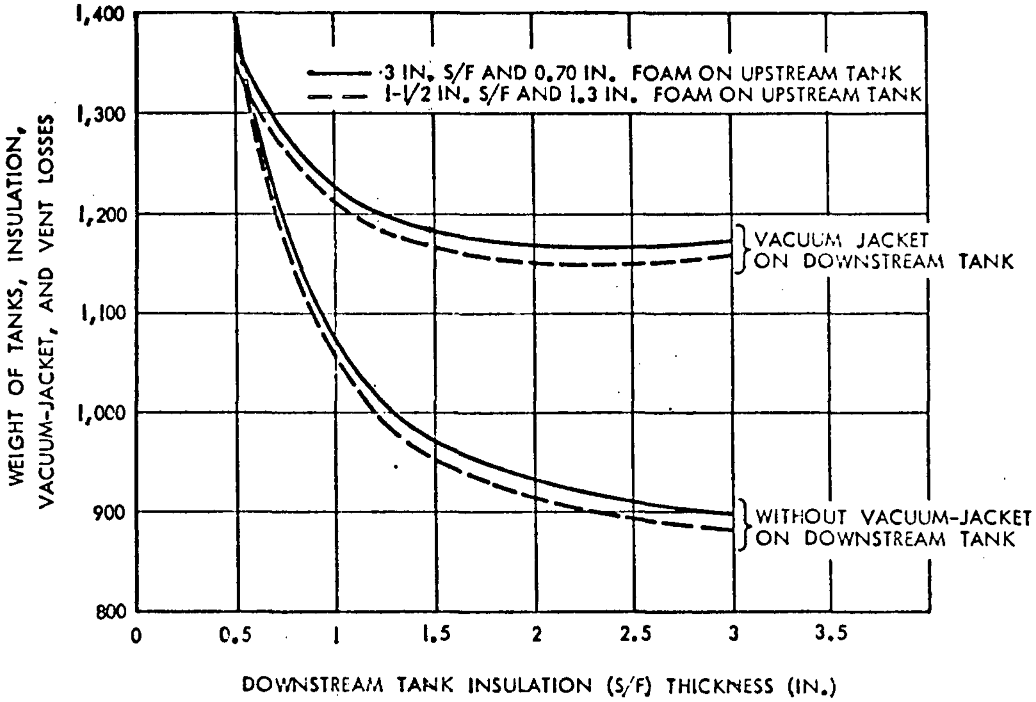


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Fig. 9.1-48 OMPS Cascade Tanks With Vapor Pressure Rise Effect of Insulation Thickness to a value corresponding to that pressure required to transfer the propellant and, thus, no engine bleed will be needed for this burn. For a 4-in. transfer-line this vapor pressure corresponds to 28 psia (4 psia ΔP above the lower tank-operating pressure of 24 psia).

9.1.3.5 Pressurization Analysis Sensitivities. Technology data regarding pressurization and experimental programs to verify pressurization approaches have not advanced the state-of-the-art to keep pace with the other cryogenic technologies. Inaccuries in the pressurization analyses and the resulting errors in design can result in significant weight penalties. An example derived from the pressurization data presented in Appendix C is presented in Fig. 9.1-49. Note that an error in a few psia in vent-pressure determination can result in as much venting error as would result from a significant error in insulation.

9.1.4 Orbit Maneuvering Propellant Supply Tradeoff Studies

Only a limited portion of the Orbit Maneuvering Propellant Supply Tradeoff Studies is presented in this section. Information principally concerns the weight analyses. As previously discussed, this section relates the Orbit Maneuvering Propellant System in a nonintegrated system where the OMPS is functioning separately.

Detailed weight statements were prepared for all OMPS approaches including the following:

1. Single Tanks - Pump at-the-Engine - GHe Pressurization - Propellants Lost After Each Engine Operation. The schematic for this subsystem is presented in Fig. 9.1-4. This was examined for:

- Engines operated 5 times and 12 times
- Vacuum-Jacketed Lines and Tanks
- Nonvacuum-Jacketed Lines and Tanks

2. Single Tank - Pump at-the-Engine - GHe Pressurization - Propellants Retained in the Lines. This was examined for:

   - Vacuum-Jacketed Lines and Tanks (see schematic in Fig. 9.1-4)
   - Nonvacuum-Jacketed Lines and Tanks

3. Single Tank - Pump at-the-Engine - GO_2/GH_2 Pressurization - Propellants Lost After Each Engine Operation. (see schematic in Fig. 9.1-5). This was examined for:

   - Engines operated 5 times and 12 times
   - Vacuum-Jacketed Tanks and Lines
   - Nonvacuum-Jacketed Tanks and Lines

4. Single Tank - Pump at-the-Engine - GO_2/GH_2 Pressurization - Propellants Retained in the Lines. This was examined for:

   - Vacuum-Jacketed Tanks and Lines
   - Nonvacuum-Jacketed Tanks and Lines

5. Single Tank - Pump at-the-Engine - GO_2/GH_2 Pressurization - Engine Idle Mode Start - Propellant Lost After Each Engine Operation. This was examined for:

   - Engines operated 5 times and 12 times
   - Vacuum-Jacketed Tanks and Lines
   - Nonvacuum-Jacketed Tanks and Lines

6. Single Tank - Pump at-the-Engine - GO_2/GH_2 Pressurization - Engine Idle Mode Start - Propellants Retained in the Lines.

   This was examined for:

   - Vacuum-Jacketed Tanks and Lines
   - Nonvacuum-Jacketed Tanks and Lines

7. Single Tank - Pump at-the-Tank - GHe Pressurization - Propellants Lost After Engine Operation. This was examined for:

   - Engines operated 5 times and 12 times.
   - Vacuum-Jacketed Tanks and Lines
   - Nonvacuum-Jacketed Tanks and Lines

8. Single Tank - Pump at-the-Tank - GHe Pressurization Propellants Retained in the Lines. This was examined for:

   - Vacuum-Jacketed Tanks and Lines
   - Nonvacuum-Jacketed Tanks and Lines

9. Single Tank - Pump at-the-Tank - GO_2/GH_2 Pressurization - Propellants Lost After Each Engine Operation. This was examined for:

   - Engines operated 5 times and 12 times
   - Vacuum-Jacketed Tanks and Lines
   - Nonvacuum-Jacketed Tanks and Lines

10. Single Tank - Pump at-the-Tank - GO_2/GHe Pressurization - Propellants Retained in the Lines. This was examined for:

    - Vacuum-Jacketed Tanks and Lines
    - Nonvacuum-Jacketed Tanks and Lines

11. Dual Tanks - Pump at-the-Engine - GHe Pressurization - Propellants Lost After Each Engine Operation (see schematic in Fig. 9.1-7). This was examined for:

- Engines operated 5 times and 12 times
- Vacuum-Jacketed Tanks and Lines
- Nonvacuum-Jacketed Tanks and Lines

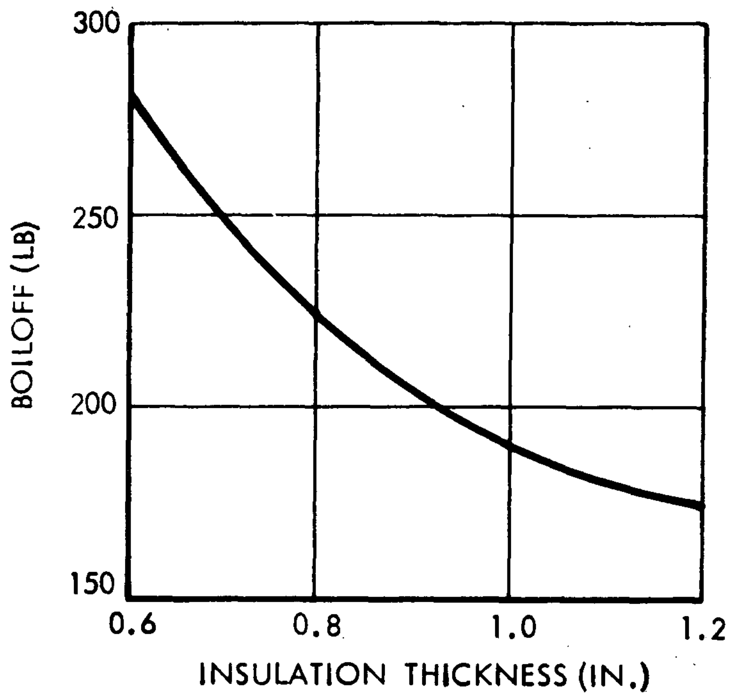
12. Dual Tanks - Pump at-the-Engine - GHe Pressurization - Propellants Retained in the Lines (see schematic in Fig. 9.1-8). This was examined for:

- Vacuum-Jacketed Tanks and Lines
- Nonvacuum-Jacketed Tanks and Lines

13. Cascade Tanks - Pump at-the-Engine - GHe Pressurization - Propellants Lost After Each Engine Operation (see schematic in Fig. 9.1-10.) This was examined for:

- Engines operated 5 times and 12 times
- Vacuum-Jacketed Tanks and Lines
- Nonvacuum-Jacketed Tanks and Lines.

GH$_2$ PRESSURIZATION (350°R – 36 PSIA)



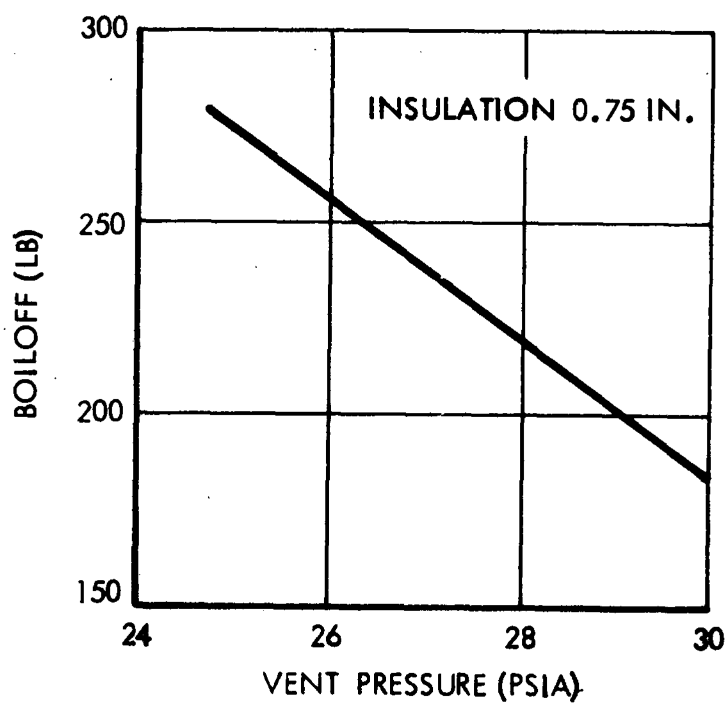


Fig. 9.1-49 Comparison of Effects on OMPS From Pressurization And Insulation Variables

The detailed weights were compiled by the following technique:

a. A list of assumptions and groundrules was compiled (Table 9.1-4) and used as a basis so that valid comparisons could be made. This compilation is based on Space Shuttle B requirements, Phase B approaches on tankage and engine installations, and standard design practices. The groundrules should be considered as reference points so comparisons can be made and are not to be considered as final.

b. System schematics were examined for the various types of OMPS sub-subsystems; component redundancy required to meet fail-operational/fail-safe criteria was incorporated. Where possible, component weights were based on AiResearch-supplied data.

c. The detailed weights were compiled by using the baseline values for LH_2 and LO_2 tankage and the optimum ullage pressures and feedline sizes generated in the single-thread subsystem tradeoff studies. These baseline values then were increased to accomodate the propellants lost through dumping or venting for cooling or chilldown purposes. Iterations of propellant tanks sizes and weights were accomplished to ensure that all factors were considered.

Weight Tradeoff Study Results

The resulting weight summaries are presented in Tables 9.1-5 through 9.1-10.

Table 9.1-4

GROUNDRULES AND ASSUMPTIONS

General Assumptions

- All tanks were sized for 3% ullage, 1% liquid residuals, and a capability of 1,815 ft/sec (2000 ft/sec - 185 ft/sec allotted to the ACPS). Impulse propellant loads were based on a ΔV capability of 1315 ft/sec and an assumed specific impulse of 444 sec.

- All pumps at-the-engine cases assumes two RL-10s installed, but line-sizing used in inert weight computations assumed only one engine operating at any given time.

- An aft location was assumed for all single tank systems. The feedline configuration was a single line from the tank, splitting near the engine and symmetrical installations from the split point to each engine inlet. All lines were the same diameter and flow lengths were 15- and 18-ft, respectively, for the oxygen and hydrogen.

- In the double tank case, the lines from the tank outlets came to a common "Y", had a short common line, and then were split with symmetrical installations going to each engine. Line-flow lengths were 6- and 9-ft., respectively.

- All systems had component redundancy to meet fail-operational/fail-safe criteria.

- All tanks contained a propellant acquisition device with restart capabilities only.

- A 5-burn mission was assumed for the one and five dump cases and a 12-burn mission for the 12 dump case.

Table 9.1-4 (Continued)

- For the helium pressurized cases, GHe was supplied to the hydrogen tank(s) at hydrogen temperature and to the oxidizer tank at oxidizer temperature (i.e., separate helium storage at the respective cryogen temperature with initial helium-storage pressure at 4000 psia).

- All comparisons were based on an RL-10 start transient in computing optimum feedline sizes and ullage pressure requirements.

- For prepressurization with vaporized propellants, all gases were stored at an interval 4000 psia at 520°R, and all prepressurant was stored (i.e., no resupply from the engine during an OMPS burn).

- Optimum insulation thicknesses were used for all tanks. These were 2- and $2\frac{1}{4}$-in. thick Superfloc on the single- and dual-hydrogen tanks, respectively; and 0.8- and 1-in. thick Superfloc on the single- and dual-oxygen tanks, respectively.

- Only hydrogen was vented for tank and line cooling. Venting was through a thermal conditioning unit (TCU), and the vented hydrogen gas was used to cool the oxidizer tank(s) and lines.

Assumptions Related Specifically to Vacuum-Jacketed Tank Cases

- All tanks and lines were considered to be vacuum-jacketed with HPI within the jacket.

- For the single dump case, the lines were prechilled on the ground and filled during ground-fill operations. Thereafter, they were maintained at cryogen temperature by vent hydrogen through an expansion valve, using the subcooled hydrogen to cool the hydrogen lines and then using the same gaseous hydrogen to cool the oxidizer lines.

Table 9.1-4 (Continued)

- For the 5- and 12-dump cases, the engine feedlines were vented between burns and chilled before OMPS operation by flowing cryogen through them. For the 5-dump case (5 burns), it was assumed that the propellant in the feedlines was in effect lost after each burn; however, where there was a short time between burns and the propellant would not be boiled out of the lines, line chilldown propellants were not required, and the propellant line was maintained chilled by replacing the propellant in the line with cold propellant from the tank.

- Hydrogen-vapor pressure was maintained at the initial vapor pressure (16 psia) by a TCU.

Assumptions Related Specifically to Nonvacuum-Jacketed Tank Cases

- All tanks and lines were insulated with HPI insulation. The tank was enclosed in Mylar purge bags, and the lines enclosed with a hard-shell (fiberglass) purge bag, and $\frac{1}{2}$-in. thick polyurethane foam was applied to the line purge-bag exterior.

- Liquid-hydrogen insulation was ground-purged with helium and LO_2 insulation with nitrogen. Both gases were supplied from the ground source and vented from the purge cavities during vehicle ascent. Purge gas venting was assumed complete when the vehicle reached an altitude pressure of 10^{-5} torr.

- No hydrogen was vented below 160,000-ft altitude.

- Hydrogen-vapor pressure was maintained as the pressure reached 22.5 psia in the tank(s) at the time venting could begin by using a TCU .

- The purge-cavity thickness was assumed to be the same as that of the insulation on the tank on the line.

Table 9.1-5

OMPS SYSTEM WEIGHT - GHe PREPRESSURIZATION AND PRESSURIZATION

Single Tank — Pump-at-Engine

Subsystem/No. of Dumps	Subsystem Weight, No. of Dumps: 1		5		12	
Ground/Flight Vent						
• Components	38		38		38	
• Lines	9		9		9	
• Line Insulation	1		1		1	
	48		48		48	
Fill/Drain & Feed						
• Valves	133		119		119	
• Lines, Incl. Bellows, etc.	163	(50)*	159	(44)*	156	(40)*
• Propellant Tanks	1260	(632)	1304	(680)	1379	(750)
• Tank Insulation	109	(154)	109	(154)	110	(155)
	1665	(969)	1691	(997)	1764	(1064)
Pressurization						
• Valves, Controls, etc.	78		78		78	
• Pressurant Storage Spheres	135		167		191	
• Lines	4		4		4	
	217		249		273	
Propellant Conditioning						
• Valves, Controls, etc.	48		48		48	
• Heat Exchangers	19		19		19	
• Acquisition Devices	60		60		60	
	127		127		127	
Subsystem Totals	2,057(1361)		2,115(1421)		2,212(1512)	
Engine Dry Weight	600		600		600	
OMPS Total Dry Weight (Lbs)	2,657(1961) *		2,715(2021) *		2,812(2112) *	

*Parenthesis refer to non-vacuum jacketed subsystems.

Table 9.1-5 (Cont'd)

	Fluid Weight No. of Dumps 1	5	12
Fluids			
• Impulse Propellants - LO_2	23,128	23,128	23,128
LH_2	4,626	4,626	4,626
• Residuals - LO_2	318	320	321
LH_2	68 (68)*	67 (68)*	68 (69)*
GO_2	138	138	138
GH_2	130 (215)	130 (215)	130 (215)
• Dumped Propellants - LO_2	52	180	276
LH_2	6	24	49
• Vented Propellants - LH_2			
Tank Cooling	116	116	116
Line Cooling	110	--	--
• Line Chilldown - LH_2	-- (27)	50 (75)	88 (110)
LO_2	-- (31)	52 (78)	80 (100)
• Engine Chilldown - LH_2	24	24	58
(RL10) - LO_2	30	30	72
• Pressurant - GH_e	97	107	117
Total Fluids (LB)	28,843	28,992	29,267
Dry Weight (Vacuum Jacketed)	2,657	2,715	2,812
Total Weight	31,500	31,707	32,079
(Non-Vacuum Jacketed)			
Total Fluids	28,986	29,129	29,395
Dry Weight	1,961	2,021	2,112
Total Weight	30,947	31,150	31,507

*Parenthesis refer to non-vacuum jacketed subsystems.

Table 9.1-6

OMPS SYSTEM WEIGHT - GO_2/GH_2 PREPRESSURIZATION AND PRESSURIZATION

Single Tank – Pump-at-Engine

Subsystem	Subsystem Weight No. of Dumps 1	5	12
Ground/Flight Vent			
• Components	38	38	38
• Lines	9	9	9
• Line Insulation	1	1	1
	48	48	48
Fill/Drain and Feed			
• Valves	133	119	119
• Lines, Incl. Bellows, etc.	163 (50)*	159 (44)*	156 (40)*
• Propellant Tanks	1,375 (711)	1,417 (753)	1,497 (817)
• Tank Insulation	104 (149)	104 (149)	104 (149)
	1,775(1043)	1,799(1065)	1,876(1125)
Pressurization			
• Valves, Controls, etc	243	243	243
• Prepressurant Storage Spheres	440	590	766
• Lines	16	16	16
	699	849	1,025
Propellant Conditioning			
• Valves, Controls, etc	48	48	48
• Heat Exchangers	19	19	19
• Acquisition Devices	60	60	60
	127	127	127
Subsystem Totals	2,649(1917)	2,823(2089)	3,076(2315)
Engine Dry Weight	600	600	600
	3,249(2517)*	3,423(2689)*	3,676(2915)*

* Parenthesis refer to non-vacuum jacketed subsystems.

Table 9.1-6 (Cont'd)

Fluids	Fluid Weight No. of Dumps 1	5	12
• Impulse Propellants - LO_2	23,128	23,128	23,128
LH_2	4,626	4,626	4,626
• Residuals - GO_2	196	240	287
GH_2	134 (170)*	135 (171)*	136 (172)*
LO_2	316	317	319
LH_2	67	67	68
• Dumped Propellants - LO_2	52	180	276
LH_2	6	24	49
• Vented Propellants -			
Tank Cooling - LH_2	187	186	185
Line Cooling - LH_2	110	-	-
• Line Childown - LH_2	- (22)	44 (66)	88 (110)
LO_2	- (28)	56 (84)	112 (140)
• Engine Childown - LH_2	24	24	58
(RL 10) - LO_2	30	30	72
• Prepressurant(*) - GO_2	229	342	458
- GH_2	3 (8)	3 (8)	4 (8)
Total Fluids (lb)	29,108	29,402	29,866
OMPS Dry Weight (lb)	3,249	3,423	3,676
(Vacuum Jacketed) Total Weight (lb)	32,357	32,825	33,542
(Non-Vacuum Jacketed) Total Fluids	29,199	29,493	29,956
Dry Weight	2,517	2,689	2,915
Total Weight	31,716	32,152	32,871

*Parenthesis refer to non-vacuum jacketed subsystems.

Table 9.1-7

OMPS SYSTEM WEIGHT – GHe PREPRESSURIZATION AND PRESSURIZATION

Single Tank – Pump-at-Tank

Subsystem/No. of Dumps	Subsystem Weight – No. of Dumps 1	5	12
Ground/Flight Vent			
• Components	38	38	38
• Lines	9	9	9
• Line Insulation	1	1	1
	48	48	48
Fill/Drain and Feed			
• Valves	104	104	104
• Lines, incl. bellows	194 (78)*	194 (78)*	194 (78)*
• Propellant Tanks	1176 (504)	1172 (502)	1177 (504)
• Tank Insulation	107 (153)	107 (153)	107 (153)
	1581 (839)	1577 (837)	1582 (839)
Pressurization			
• Valves, controls, etc.	80	80	80
• Pressurant Storage Spheres	55	55	55
• Lines	4	4	4
	139	139	139
Propellant Conditioning			
• Valves, controls, etc.	50	50	50
• Heat Exchangers	19	19	19
• Acquisition Devices	60	60	60
	129	129	129
Subsystem Totals	1,897(1115)	1,893(1153)	1,898(1155)
Thruster Dry Weight	320	320	320
Turbopump Dry Weight	190	190	190
Total Dry Weight	2,407(1665)*	2,403(1663)*	2,408(1665)*

*Parenthesis refer to non-vacuum jacketed subsystems.

Table 9.1-7 (Cont'd)

Fluids	**Fluid Weight No. of Dumps** 1	5	12
• Impulse Propellants - LO_2	23128	23128	23128
- LH_2	4626	4626	4626
• Residuals - LO_2	317	318	319
- LH_2	66 (67)*	66 (67)*	66 (67)*
- GO_2	143	143	143
- GH_2	136 (192)	135 (191)	136 (192)
• Dumped Propellants - LO_2	6	29	69
LH_2	1	2	5
• Vented Propellants - Tank Cooling-LH_2	115 (116)	114 (116)	115 (116)
Line " "	55	-	-
• Line Childown - LH_2	- (4)	8 (12)	16 (20)
LO_2	- (8)	16 (24)	32 (40)
• Pump Childown - LH_2	20	20	48
LO_2	28	28	66
• Pressurant - GHe	34	34	34
Vacuum Jacketed			
Total Fluids	28,675	28,667	28,803
Dry Weight	2,407	2,403	2,408
Total System Weight (lbs)	31,082	31,070	31,211
Non-Vacuum Jacketed			
Total Fluids	28,745	28,738	28,873
Dry Weight	1,665	1,663	1,665
Total System Weight	30,410	30,401	30,538

*Parenthesis refer to non-vacuum jacketed subsystems.

Table 9.1-8

OMPS SYSTEM WEIGHT - GO_2 / GH_2 PREPRESSURIZATION AND PRESSURIZATION

Single Tank - Pump-at-Tank

Subsystem	Subsystem Weight, No. of Pumps: 1		5		12	
Ground/Flight Vent						
• Components	38		38		38	
• Lines	9		9		9	
• Line Insulation	1		1		1	
	48		48		48	
Fill/Drain & Feed						
• Valves	104		104		104	
• Lines, Incl. Bellows, etc.	194	(78)*	194	(78)*	194	(78)*
• Propellant Tanks	1270	(659)	1273	(651)	1278	(658)
• Tank Insulation	104	(149)	104	(149)	104	(149)
	1672	(990)	1675	(982)	1680	(989)
Pressurization						
• Valves and Switches	243		243		243	
• Prepressurant Storage Spheres	192		192		192	
• Lines	36		36		36	
	471		471		471	
Propellant Conditioning						
• Valves, Controls, etc.	48		48		48	
• Heat Exchangers	19		19		19	
• Acquisition Devices	60		60		60	
	127		127		127	
Subsystem Totals	2,318	(1636)	2,321	(1628)	2,326	(1635)
Thruster Dry Weight	320		320		320	
Turbo Pump Dry Weight	190		190		190	
OMPS Total Dry Weight (Lbs)	2,828	(2146)*	2,831	(2138)*	2,836	(2145)*

*Parenthesis refer to non-vacuum jacketed subsystems.

Table 9.1-8 (Cont'd)

	Fluid Weight No. of Dumps 1	5	12
Fluids			
• Impulse Propellants - LO_2	23,128	23,128	23,128
LH_2	4,626	4,626	4,626
• Residuals - GO_2	124	124	124
GH_2	111 (138)*	111 (138)*	111 (138)*
LO_2	317	317	318
LH_2	68	67	67
• Dumped Propellants - LO_2	6	29	69
LH_2	1	2	5
• Vented Propellants - LH_2			
Tank Cooling	194	194	194
Line Cooling	55	--	--
• Line Chilldown - LH_2	-- (4)	8 (12)	16 (20)
LO_2	-- (8)	16 (24)	32 (40)
• Pump Chilldown - LH_2	20	20	48
LO_2	28	28	66
• Prepressurant - GO_2	42	42	42
GH_2	2 (5)	2 (5)	2 (5)
Total Fluids (Lb)	28,722	28,714	28,848
OMPS Dry Weight (Lb)	2,828	2,831	2,836
(Vacuum Jacketed) Tanks Total Weight (Lb)	31,550	31,545	31,684
(Non-Vacuum Jacketed)			
Total Fluids	28,764	28,756	28,890
OMPS Dry Weight	2,146	2,138	2,145
Total Weight	30,910	30,894	31,035

*Parenthesis refer to non-vacuum jacketed subsystems.

Table 9.1-9

OMPS SYSTEM WEIGHT - GHe PREPRESSURIZATION AND PRESSURIZATION

Dual Tanks - Pump-at-Engine

Subsystem/No. of Dumps	Subsystem Weight — No. of Dumps: 1	5	12
Ground/Flight Vent			
• Components	28	28	28
• Lines	57 (20)*	57 (20)*	57 (20)*
• Line Insulation	2 (10)	2 (10)	2 (10)
	87 (58)	87 (58)	87 (58)
Fill/Drain and Feed			
• Valves	90 (174)	255 (267)	255 (267)
• Lines, incl. Bellows	251 (106)	251 (106)	251 (106)
• Propellant Tanks	1505 (656)	1498 (651)	1518 (663)
• Tank Insulation	162 (222)	159 (220)	163 (224)
	2008 (1158)	2163 (1244)	2187 (1260)
Pressurization			
• Valves, controls, etc.	58	58	58
• Pressurant Storage Spheres	161	159	162
• Lines	6	6	6
	225	223	226
Propellant Conditioning			
• Valves, controls, etc.	53(102)	90	90
• Heat Exchangers	32	25	25
• Acquisition Devices	92	92	92
	177	207	207
Subsystem Totals	2,497(1667)	2,680(1732)	2,707(1751)
Engine Weight	600	600	600
Total System Dry Weight (lbs)	3,097(2267)*	3,280(2332)*	3,307(2357)*

*Parenthesis refer to non-vacuum jacketed subsystems.

Table 9.1-9 (Cont'd)

Fluids	Fluid Weight No. of Dumps 1	5	12
• Impulse Propellants - LO_2	23128	23128	23128
- LH_2	4626	4626	4626
• Residuals - LO_2	318	320	325
- LH_2	67 (68)*	67	68 (69)*
- GO_2	143	144	146
- GH_2	138 (194)*	136 (192)*	139 (196)
• Dumped Propellants - LO_2	50	249	599
- LH_2	5	23	54
• Vented Propellants - Tank Cooling - LH_2	122 (124)	120 (122)	123 (126)
- Line " "	132	-	-
• Line Chilldown - LH_2	- (22)	44 (66)	88 (110)
- LO_2	- (28)	56 (84)	112 (140)
• Engine Chilldown - LH_2	24	24	58
(RL10) - LO_2	30	30	72
• Pressurant - GH_e	109 (110)	108 (109)	110 (112)
Vacuum Jacketed			
Total Fluids (lbs)	28,892	29,075	29,648
System Dry Weight	3,097	3,280	3,307
Total System Weight (lbs)	31,989	32,355	32,955
Non-Vacuum Jacketed			
Total Fluids	29,002	29,184	29,761
Dry Weight	2,267	2,332	2,351
Total System Weight (lbs)	31,269	31,516	32,112

*Parenthesis refers to non-vacuum jacketed subsystems.

Table 9.1-10

OMPS SYSTEM WEIGHT - GHe PREPRESSURIZATION AND GHe/ENGINE BLEED PRESSURIZATION

Cascaded Tanks - Pump at-the-Engine

Subsystem	Subsystem Weight, No. of Dumps: 5		Subsystem Weight, No. of Dumps: 12	
Ground/Flight Vent				
• Components	77		77	
• Lines	9		9	
• Line Insulation	1		1	
	87		87	
Fill/Drain & Feed				
• Valves	330		317	
• Lines, incl. Bellows, etc.	333	(84)*	-	(80)*
• Propellant Tanks	1231	(758)	-	(825)
• Tank Insulation	270	(323)	-	(328)
	2164	(1495)	-	(1550)
Pressurization				
• Valves, Controls, etc.	196		196	
• Pressurant Storage Spheres	120		140	
• Lines	16		16	
	332		352	
Propellant Conditioning				
• Valves, Controls, etc.	66		66	
• Heat Exchangers	13		13	
• Acquisition Device	11		11	
	90		90	
Subsystem Totals	2673	(2004)	-	(2079)
Engine Dry Weight	600		600	
OMPS Total Dry Weight (lb)	3273	(2604)*	-	(2679)*

*Parenthesis refers to non-vacuum jacketed subsystems.

Table 9.1-10 (cont.)

		No. of Dumps 5		12	
Fluids					
• Impulse Propellants	LO_2	23,128		23,128	
	LH_2	4,626		4,626	
• Residuals	LO_2	344	(344)*	-	(346)*
	LH_2	72	(72)	-	(73)
	GO_2	135		135	
	GH_2	80		80	
• Dumped Propellants	LO_2	180		276	
	LH_2	24		49	
• Vented Propellants - Tank Cooling	LH_2	209	(217)	-	(217)
	GO_2 (Upper Tank)	116		148	
	GH_2 (Upper Tank)	106		106	
• Line Childown	LH_2	50	(75)	-	(110)
	LO_2	52	(78)	-	(100)
• Engine Childown	LH_2	24		58	
	LO_2	30		72	
• Pressurant	GHe	83		89	
(Vacuum Jacketed)					
Total Fluids		29,259		-	
Dry Weight		3,273		-	
Total Weight		32,532		-	
(Nonvacuum Jacketed)					
Total Fluids		29,318		29,613	
Dry Weight		2,604		2,679	
Total Weight		31,922		32,292	

*Parenthesis refers to non-vacuum jacketed subsystems.

9.2 ORBIT INJECTION PROPELLANT SUPPLY (OIPS)

The Orbit Injection Propellant Supply analyses and evaluations did not involve the tradeoff of entire subsystems because of the dependency of the subsystems upon vehicle design. Tradeoff studies were principally directed at examining particular problems. The overall approach involved in the OIPS System Analyses is presented in Fig. 9.2-1.

9.2.1 Selection of Candidates For Investigations

Location of the tankage in the orbiters is presented in Section 5. The investigations selected for examination were mainly the result of NASA-MSC requests. For the most part, analyses were directed at the sensitivity examination of factors associated with thermal protection, pressurization, line sizing, feedline cooling, etc.

A summation of Orbit Injection Propellant Supply factors is presented in Fig. 9.2-2.

9.2.1.1 Schematics for Component Evaluations at AiResearch. Schematics for the OIPS (see Appendix E) were prepared and submitted to AiResearch for the selection of components. The schematics were formulated to represent the possible component arrangements and for use in performing the initial redundancy analyses, using the SETA II computer program. The identified redundancies, presented in Appendix E, identified the least-reliable components in the subsystems.

9.2.2 Detailed Subsystem Analyses and Sensitivity Studies

Because of the nature of the investigations and evaluations performed for the OIPS, the analyses and sensitivity studies are closely related and are presented in the same section of the report.

9.2.2.1 Orbit Injection Propellant Supply Prepressurization. Whether or not it is necessary to vent the propellant tanks during ascent and prior to engine start is dependent upon several factors:

- Desired tank design pressure (which is difficult to determine for load-carrying tanks)
- Insulation
- Acceleration at the time of engine start (affecting required ullage pressure).

If the liquid-oxygen orbit-injection tank is to vent during ascent, and the liquid-hydrogen tank is to vent at some point out of the atmosphere, on-board prepressurization for engine start will be necessary. The requirement is reduced if engine start is initiated under acceleration. If the tanks are not vented, then the alternative is prepressurization with helium prior to launch with possible resulting penalties from maximum tank pressures.

Combined weights of prepressurization gas and storage spheres for the OIPS liquid-hydrogen and liquid-oxygen tanks have been examined for a range of storage pressures. The analysis considered both helium and gaseious hydrogen for the LH_2 tanks, and both helium and gaseous oxygen for the LO_2 tanks. Figures 9.2-3 through 9.2-6 show the sphere characteristics versus storage pressure for each combination of pressurant and propellant studied.

Figures 9.2-3 and 9.2-4 indicate a small difference between helium and hydrogen as pressurants for the LH_2 tanks. The case of hydrogen pressurant results in a little lower storage-volume requirement. As noted from the physical data presented above, this prepressurization quantity provides for the condition of LH_2 temperature-stratification in the tank, which condition will exist at the time of engine start.

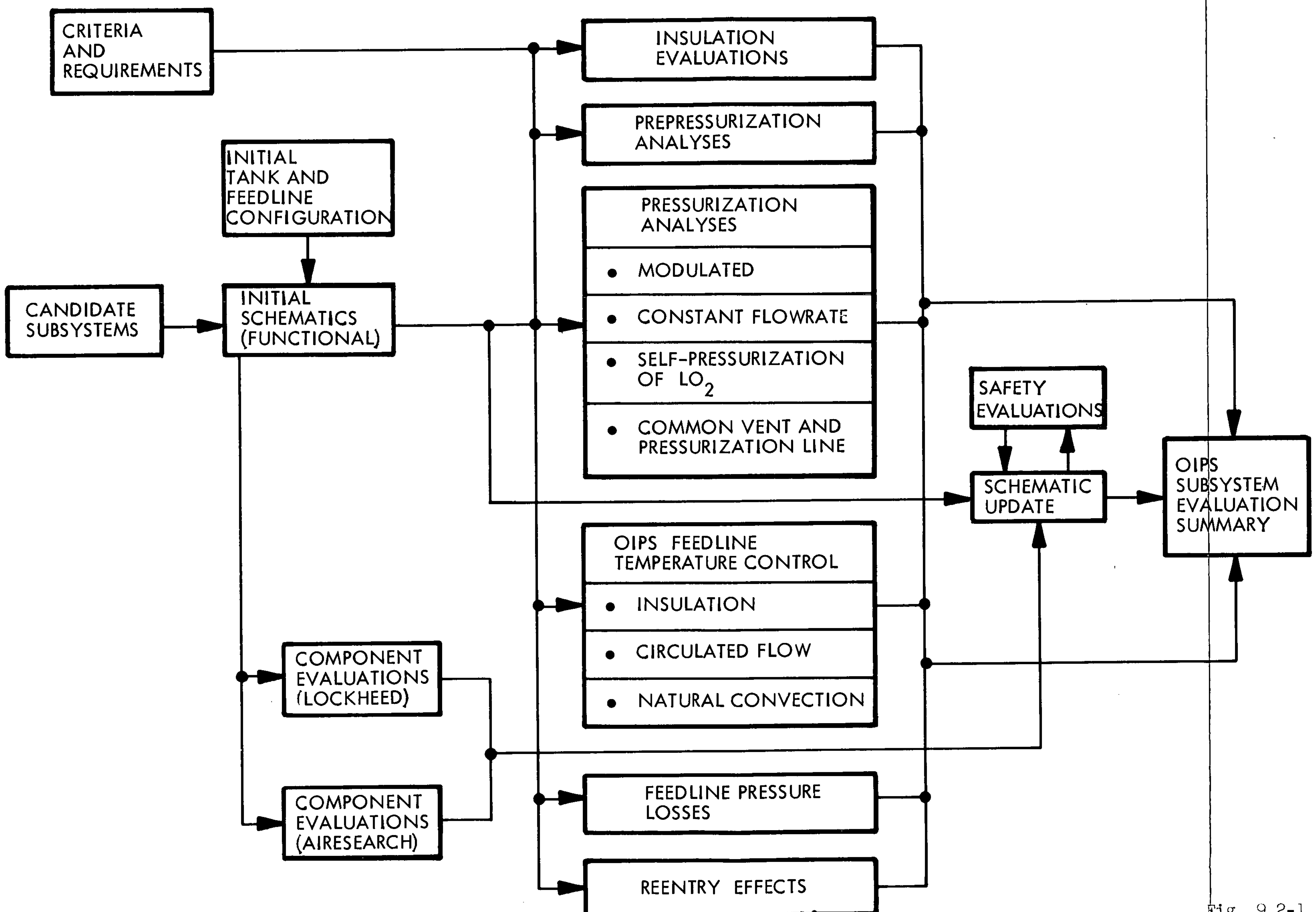


Fig. 9.2-1 Approach to Orbit Injection Propellant Supply Evaluations

FOLDOUT FRAME 1

FOLDOUT FRAME 2

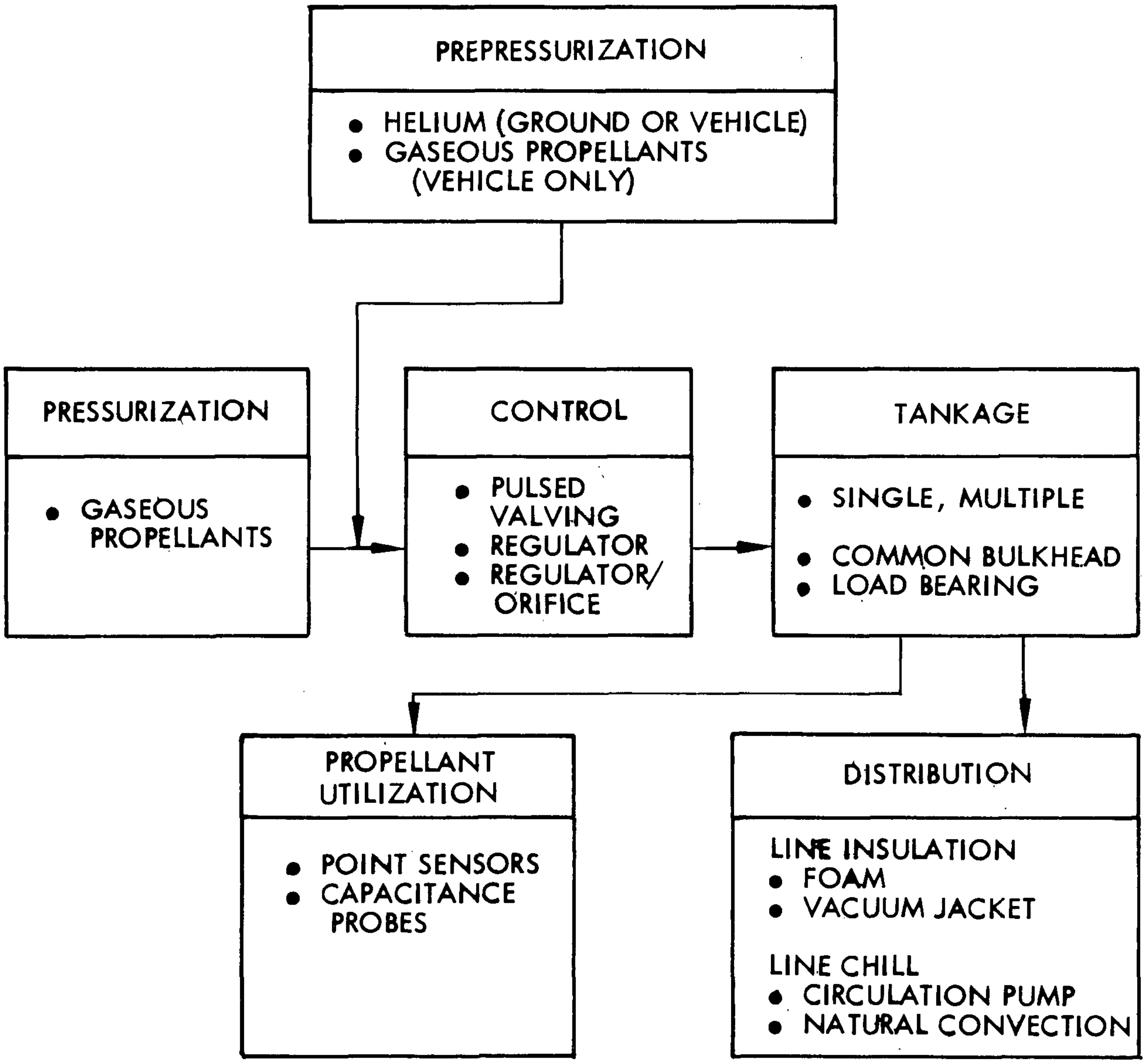


Fig. 9.2-2 Orbit Injection Propellant Supply

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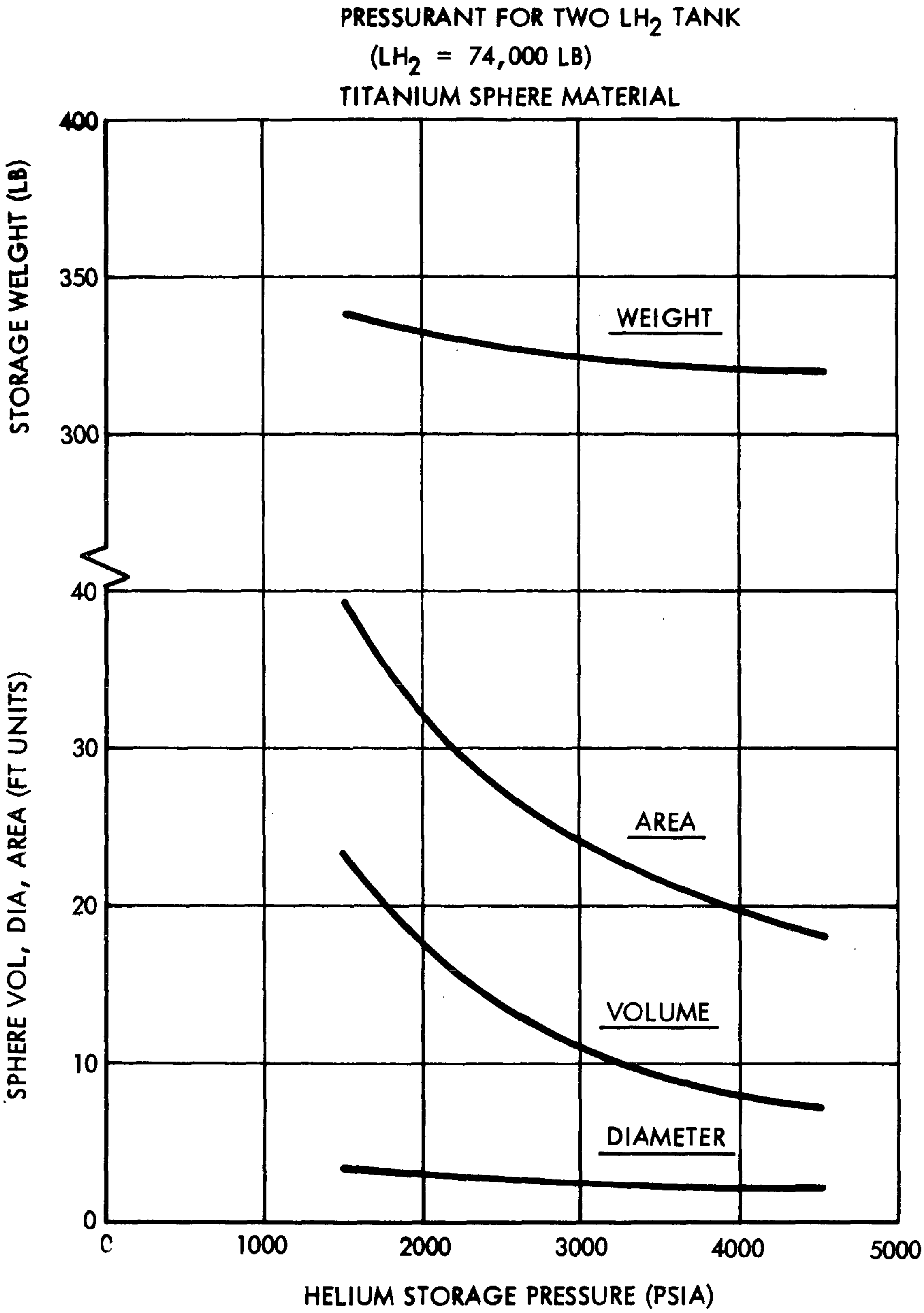

Fig. 9.2-3 Sphere Characteristics - GH_2 Pressurized LH_2 Tanks

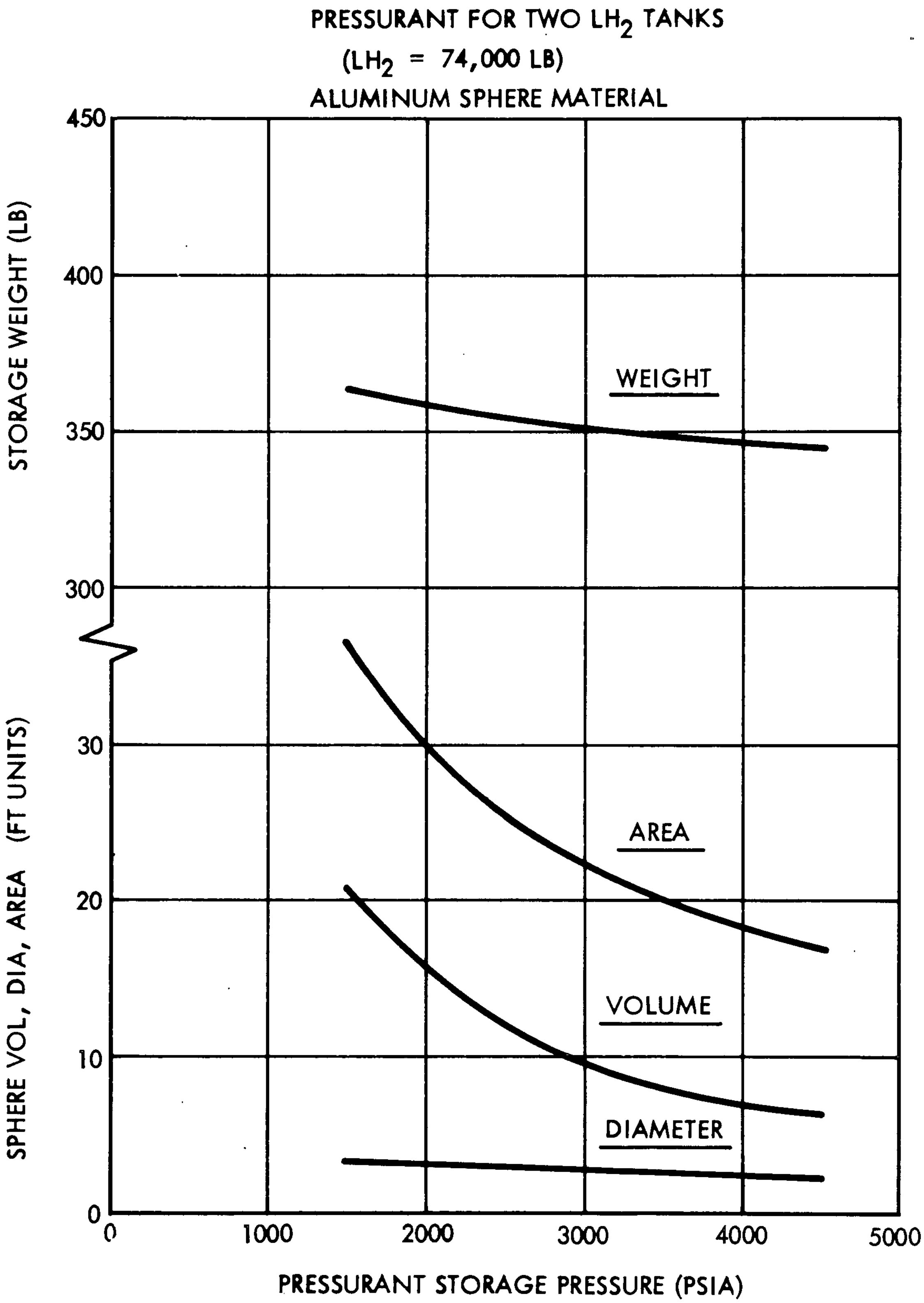

Fig. 9.2-4 Sphere Characteristics - GH_2 Pressurized LH_2 Tanks

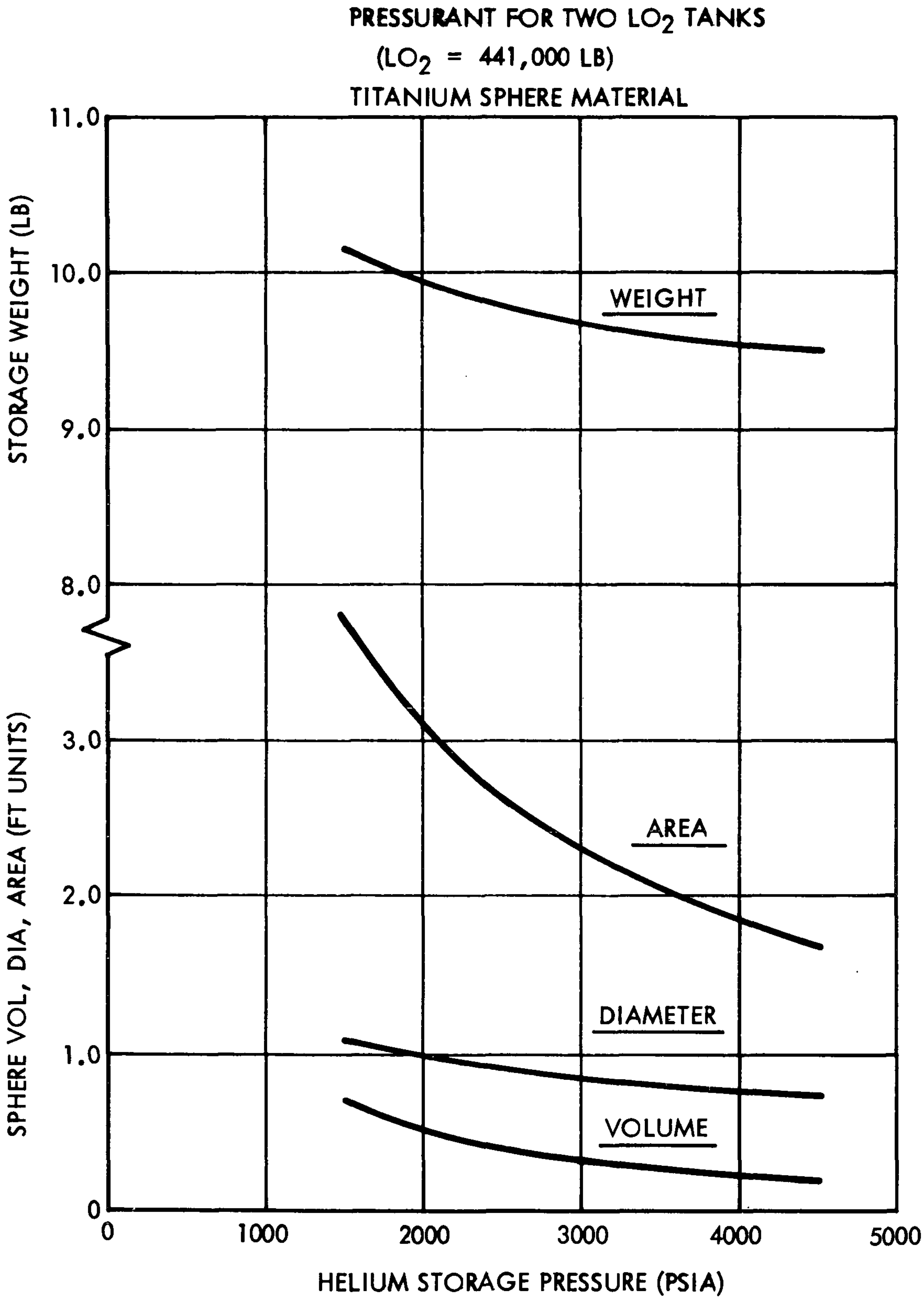

Fig. 9.2-5 Sphere Characteristics - Helium Pressurized LO_2 Tanks

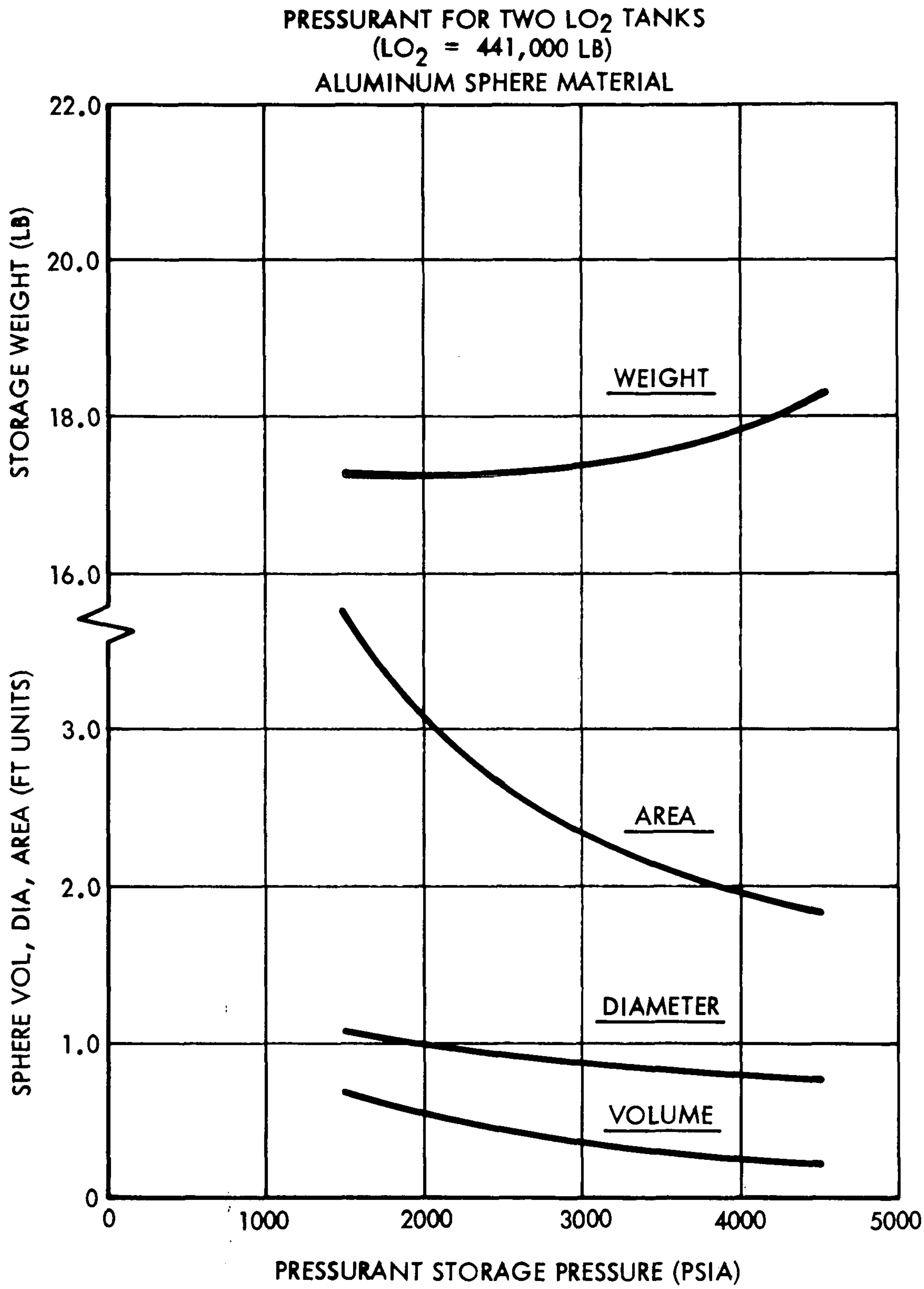

Fig. 9.2-6 Sphere Characteristics - Helium Pressurized LO_2 Tanks

Figures 9.2-5 and 9.2-6 indicate small prepressurization requirements of the two LO_2 tanks. The sphere volume requirements for helium and oxygen pressurants are nearly equal, but the system weights differ due to the use of aluminum for the oxygen sphere and the difference in gas specific weights. For either pressurant, the very small quantity required is largely due to the favorable temperature-stratification in the tank, caused in part by the cooling effect of the LO_2/LH_2 common bulkhead at the drain end of the LO_2 tank. If equal temperatures of $165^{o}R$ existed throughout the LO_2, the pressurant gas requirement would be about five-to-ten times as great, for either gas.

A summary of the prepressurization storage weights is presented in Figs. 9.2-7 and 9.2-8. It appears helium or propellant-gas pressurization is of comparable weight.

9.2.2.2 Orbit Injection Propellant Supply Pressurization. The pressurization analyses were conducted employing several approaches:

- Pressurization system, in which the flow can be modulated and the pressurant inlet temperature held constant.

- Pressurization system, in which both the flowrate and the temperature are held constant.

- Self-pressurization of the liquid-oxygen tanks.

The pressurization analyses were conducted considering propellant stratification. Analyses were made possible through the use of the LMSC Asymmetric Propellant Heating Code. This program computes a numerical solution to equations describing the pressurization, liquid-ullage coupling, and thermal stratification processes as a function of time in a propellant tank experiencing a time-varying acceleration and sidewall heat flux.

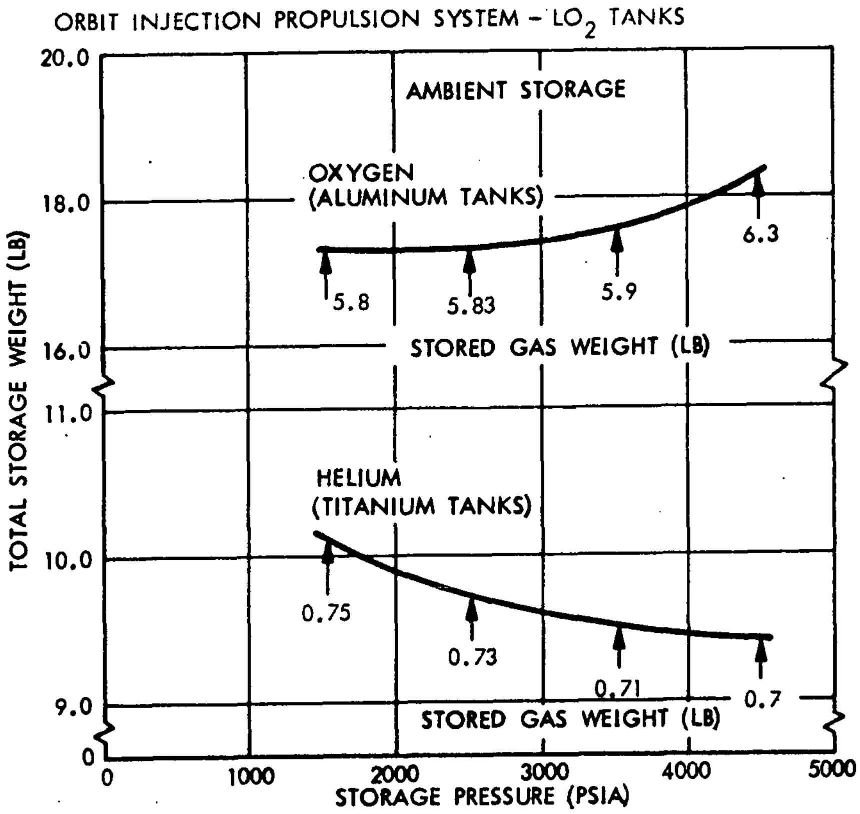

Fig. 9.2-7 Onboard Prepressurization

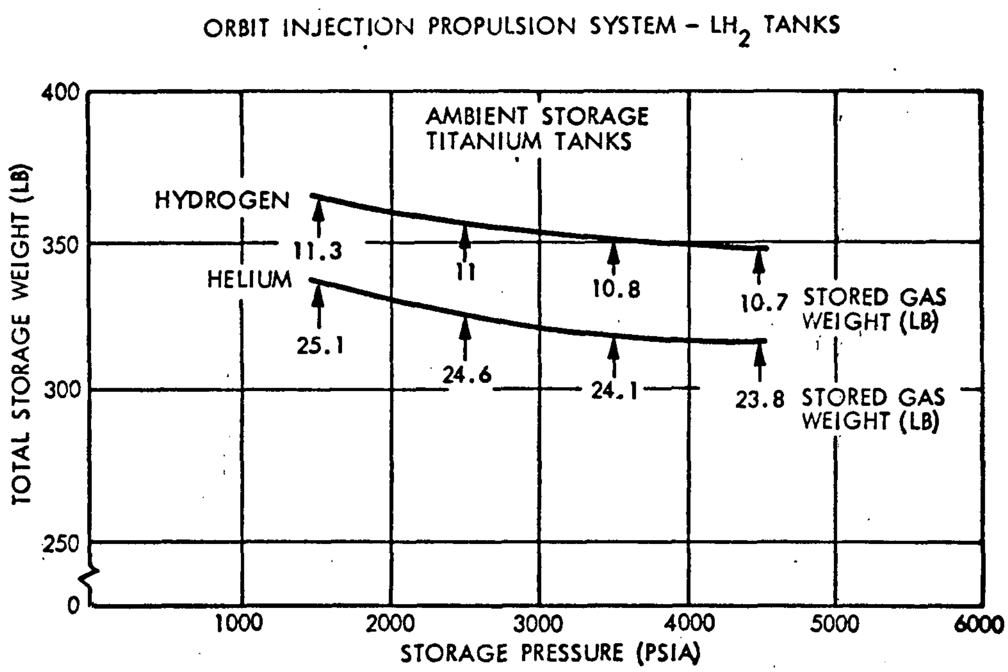

Fig. 9.2-8 Onboard Prepressurization

9.2.2.2.1. Modulated Pressurization. The pressurization analytical results employing modulated pressurant flowrate are presented in Appendix C. Analyses were conducted for various insulation thicknesses and inlet temperatures. The tank configurations employed in the analyses were the McDonnell-Douglas Phase B orbiter tanks.

The effects of stratification can be seen in Figures C-43 and C-44 in Appendix C. The most important weight factor in the evaluations is the residual-vapor mass. As noted in Appendix C, all of the parameters examined show a relatively small effect from variation in insulation thickness. The effects of inlet temperature and vent pressure are very significant.

9.2.2.2.2. Constant Flowrate Pressurization. The constant flowrate pressurization was examined principally as a comparison to the modulated flowrate pressurization. Engine data were examined, and the pressurant conditions selected for examination were:

- LO_2 - 1.5 lb/sec - 700°R
- LH_2 - 0.5 lb/sec - 500°R

Analyses were made using the Asymmetric Propellant Heating Computer Program and one McDonnell-Douglas Tank as shown in Appendix C. Excess propellant-gas flow was vented. The analyses were made as a function of insulation thickness.

The two most important parameters for examination were (1) the weight of the residual gas and (2) the quantity of gas vented.

Results of the residual-gas weight analyses for oxygen are presented in Figure 9.2-9. This is compared to modulated-flow pressurization data. As seen from this comparison, there is a negligible residual-gas penalty or no penalty at all for the use of a constant flowrate pressurization in the liquid-oxygen tank. The other portion of the penalty is the vented-gas weight. Results of the oxygen analyses are presented in Fig. 9.2-10.

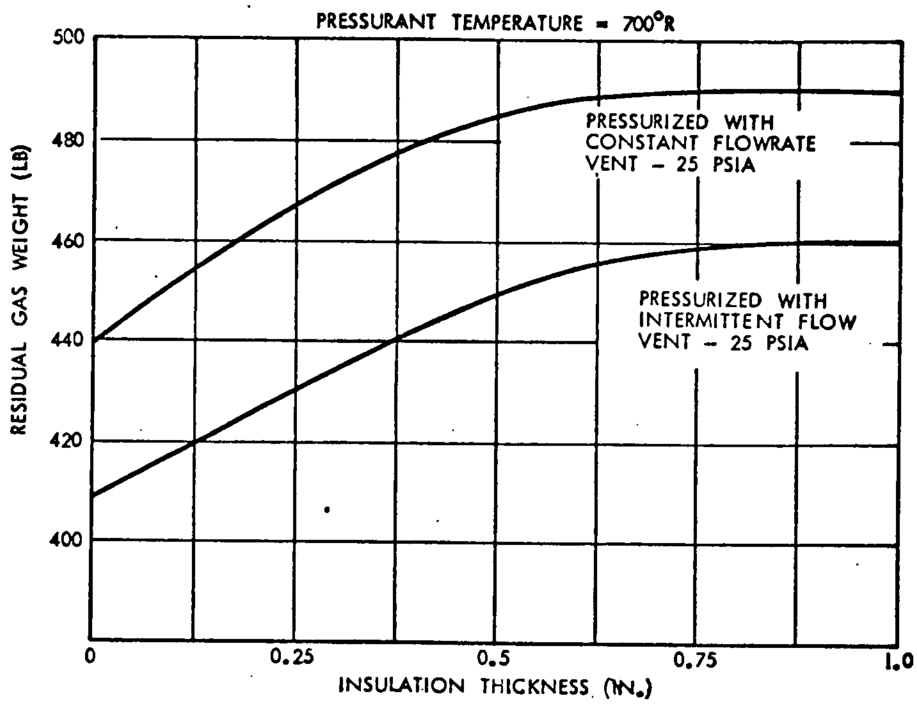

Fig. 9.2-9 Comparison of OIPS Pressurization Methods (Oxygen Tank Residuals per Tank)

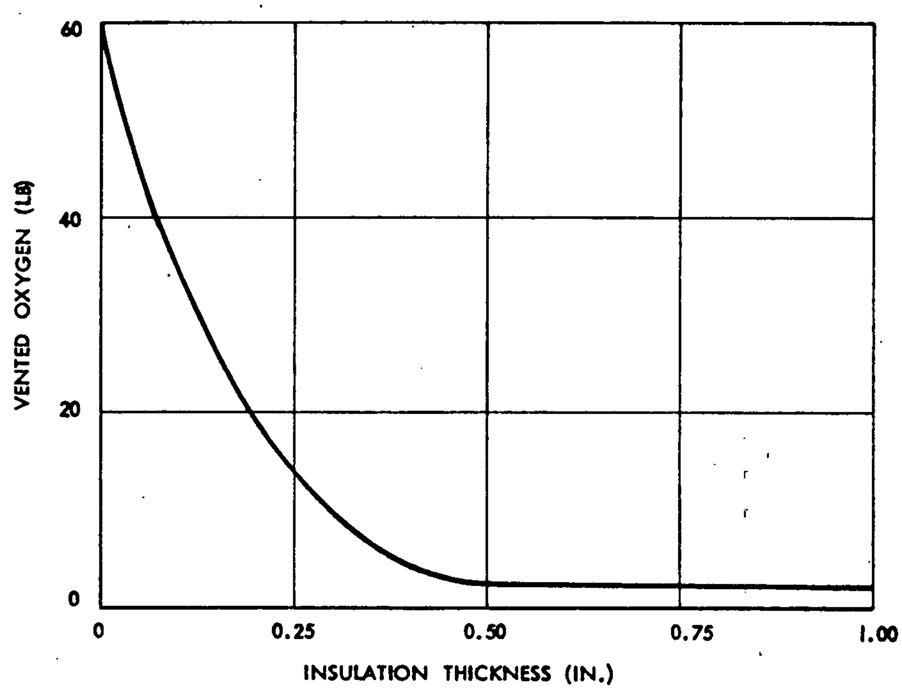

Fig. 9.2-10 OIPS Oxygen Tank Vented Weight per Tank With Constant Flowrate Pressurization

The penalty, approximately 60 lb/tank (120 lb/vehicle) for the noninsulated liquid-oxygen tanks, is considered to be relatively small.

Results of the residual liquid-hydrogen evaluations are presented in Fig. 9.2-11. In comparison with intermittent modulated flow, the pressurization with constant flowrate produced a lower residual-gas weight. The quantity of hydrogen vented, shown in Fig. 9.2-12, is negligible.

9.2.2.2.3. Self-Pressurization of the Liquid-Oxygen Tanks. The liquid-oxygen tanks, particularly with the oxygen forward, offer the potential of self-pressurization - i.e., it is not necessary for gas to be added to the tanks. Analyses used the stratification computer programs and the McDonnell-Douglas LO_2 configurations presented in Appendix C.

Results of the ullage pressure determinations are presented in Fig. 9.2-13 for no insulation and in Fig. 9.2-14 for an insulation thickness of one inch. These curves indicate that sufficient ullage pressure is available for engine start for the no insulation case, but if the liquid-oxygen tank is insulated, sufficient ullage pressure is unavailable.

Another consideration is the liquid-oxygen temperature at the tank exit, which is the principal factor determining the pressure required to provide NPSH. From examination of Fig. 9.2-15, the maximum temperature in the tank bottom results in a vapor pressure of less than 19 psia. The available hydrostatic head would normally be sufficient to maintain NPSH (dependent upon the line design).

The residual-vapor weight (shown in Fig. 9.2-16) would be approximately 350 lb/tank, which appears to be comparable with normal hot-gas pressurization with vent pressures near 25 psia, as presented in Appendix C.

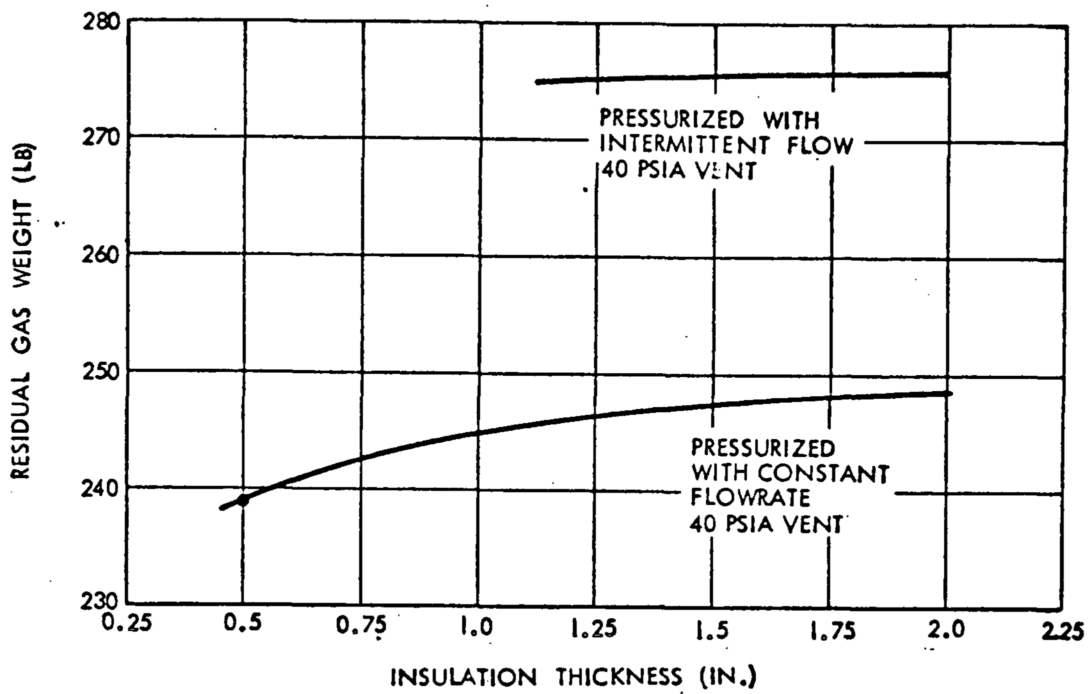

Fig. 9.2-11 Comparison of OIPS Pressurization Methods (Hydrogen Tank Residuals per Tank)

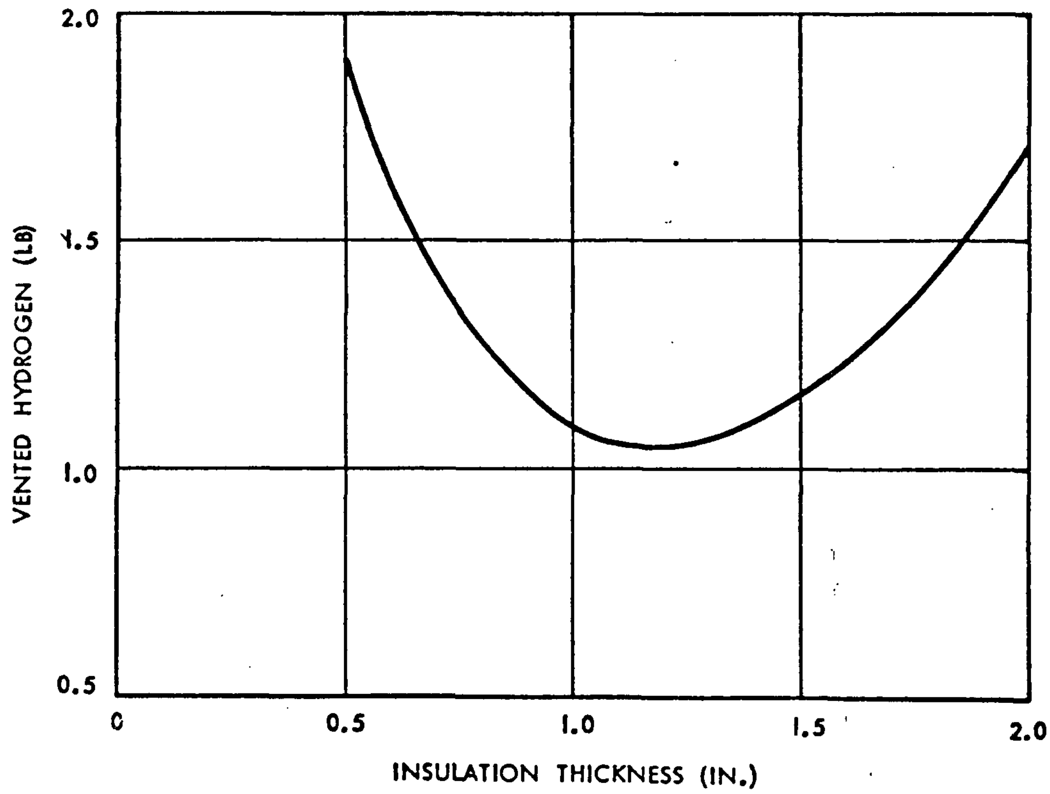

Fig. 9.2-12 OIPS Hydrogen Tank Vented Weight per Tank (With Constant Flowrate Pressurization)

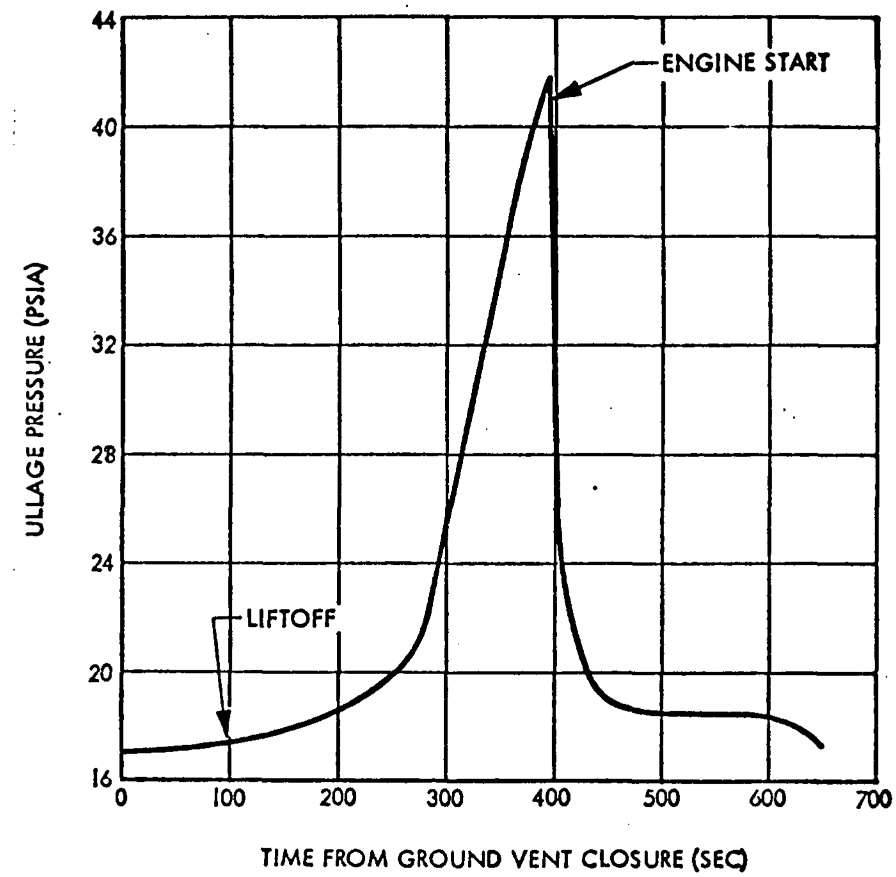

Fig. 9.2-13 Self-Pressurized LO_2 Orbit-Injection Tank - No Insulation

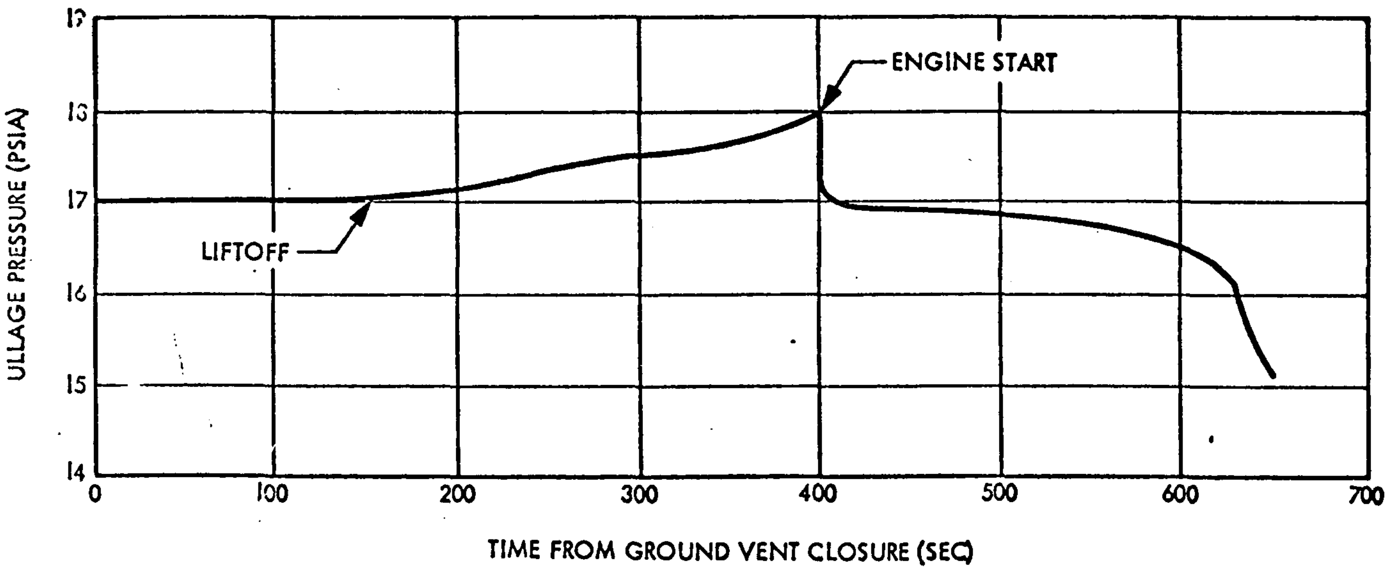

Fig. 9.2-14 Self-Pressurized LO_2 Orbit-Injection Tank - 1 In. Insulation

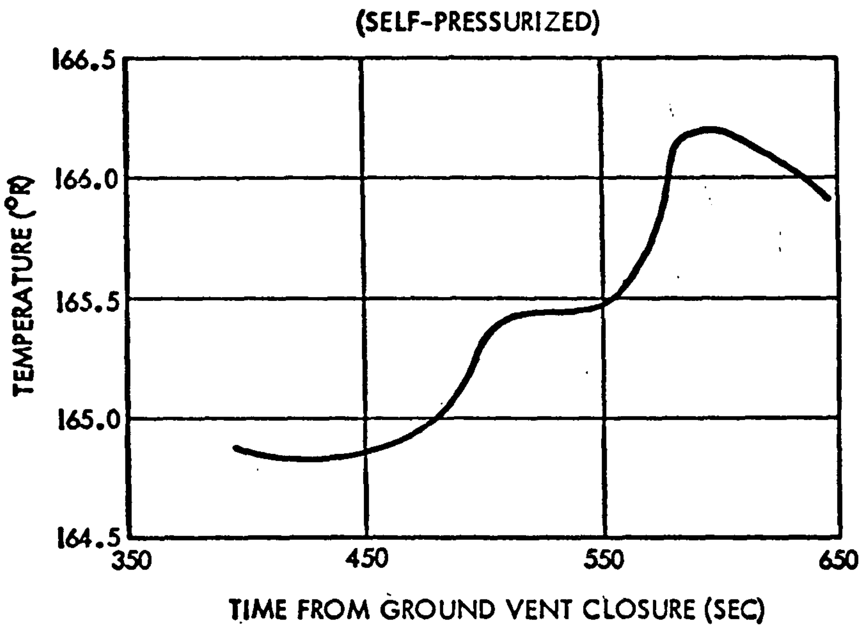

Fig. 9.2-15 Ascent-Tank Drained-Liquid Temperature

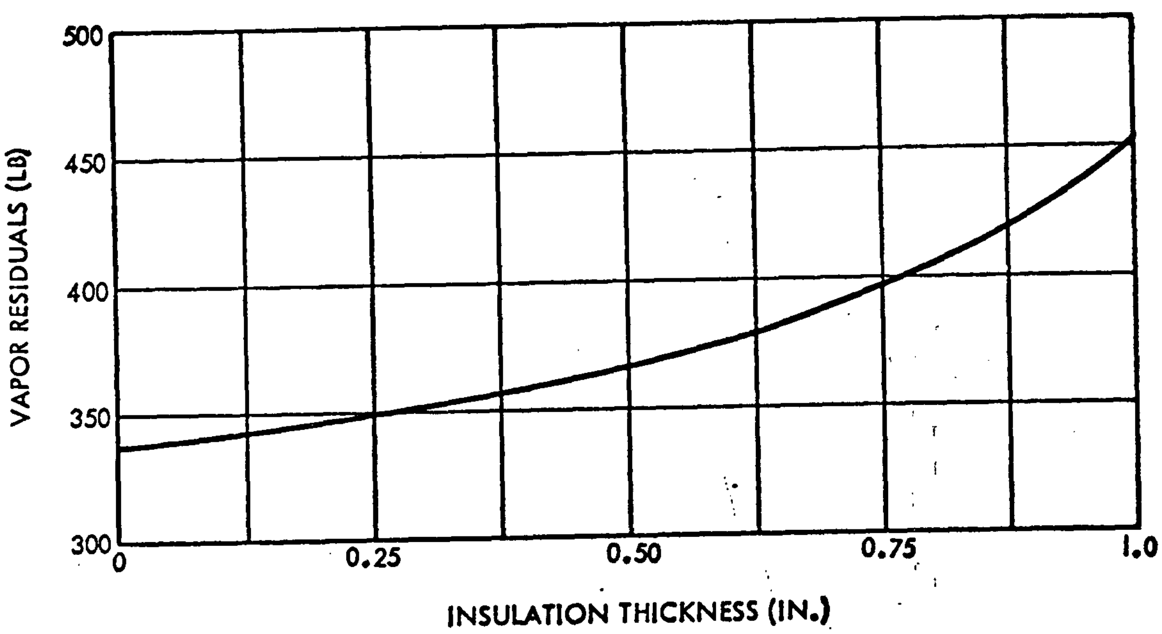

Fig. 9.2-16 Self-Pressurized LO_2 Orbit-Injection Tank Vapor Residuals vs Insulation Thickness

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9.2.2.3. Evaluation of Common Vent and Pressurization Line. An evaluation was made of the use of a common pressurization and venting line (Fig. 9.2-17) as compared to separate pressurization and venting lines (Fig. 9.2-18). The approach was to generate extensive parametric data and make generalized conclusions.

9.2.2.3.1 Prepressurization System. An analysis was performed to determine stagnation pressure at the beginning of the pressurization as a function of the line diameter and length. This pressure is an indication of the pressure drop through the line. The pressure must be low enough to assure that the engine orifice is operating under choked-flow conditions at all times. The mass-flow rate selected for the O_2 pressurization was 4.5 lb/sec, which corresponds to three engines each supplying 1.5 lb/sec. Correspondingly, the H_2 mass-flow rate was 1.5 lb/sec, which corresponds to three engines each supplying 0.5 lb/sec. Total temperature for the O_2 side was 900°R and for the H_2 side was 500°R, which corresponds to the Rocketdyne engine at the normal power level. The resulting curves for Po_3 (stagnation pressure at the beginning of the pressurant line) as a function of line diameter for various line lengths are shown in Figs. 9.2-19 and 9.2-20 for oxygen and Figs. 9.2-21 and 9.2-22 for hydrogen.

For the normal power-level engine setting and the engine-flow rates stated above, the engine bleed pressures for the Rocketdyne engine are 5,100 psia for O_2 and 3,700 psia for H_2. With these feed pressures, the maximum pressure at the beginning of the pressurization must be less than 2,700 psia for O_2 and 1,950 psia for H_2.

9.2.2.3.2. Vent System. The vent system line provides (1) propellant tank venting during the fill operation, steady-state boiloff mode, and (2) bleedoff of excess pressurant flow during engine operation. Analyses were performed to determine the required line size for these modes of operation.

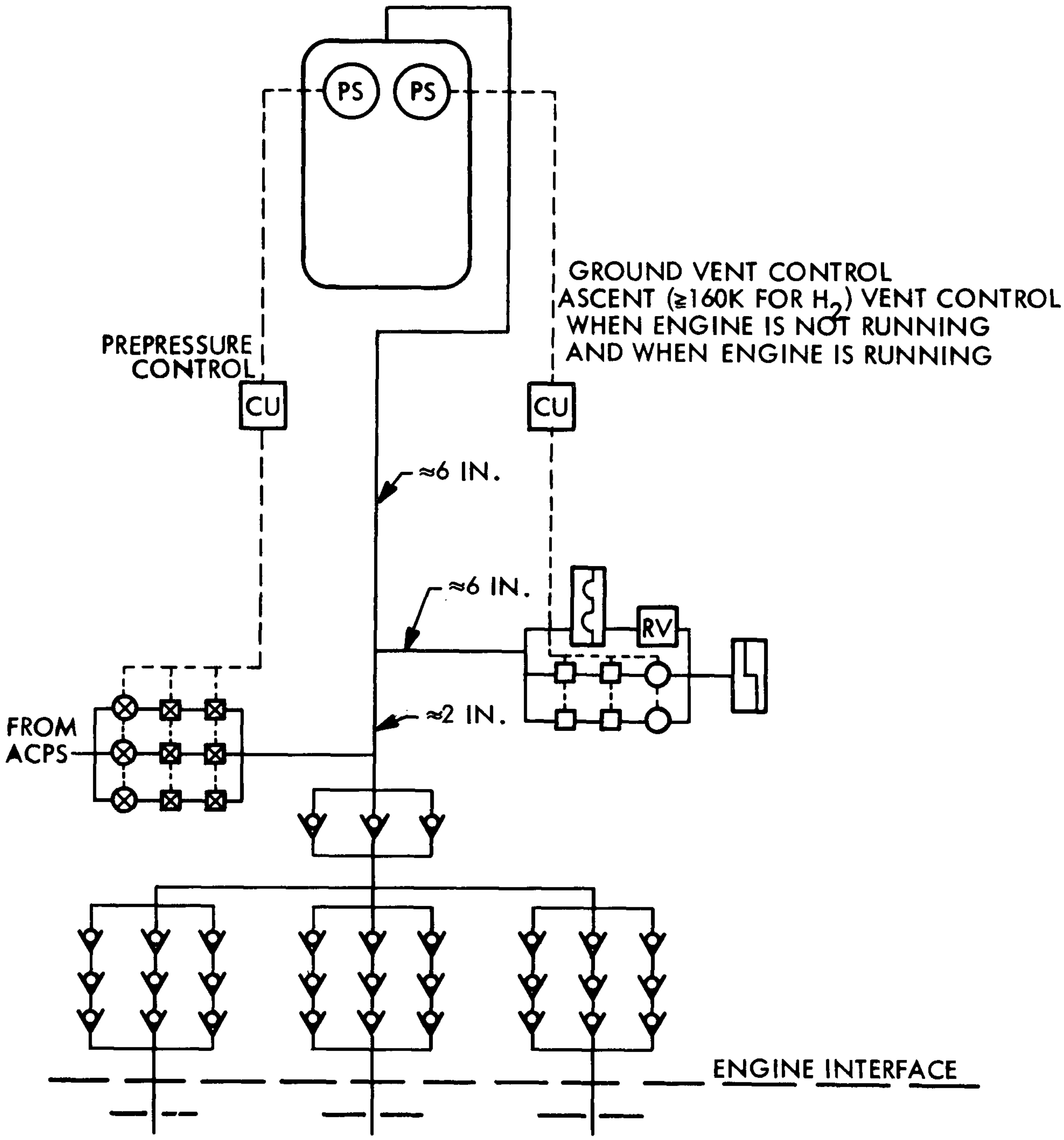

Fig. 9.2-17 Common Pressurization and Vent Lines

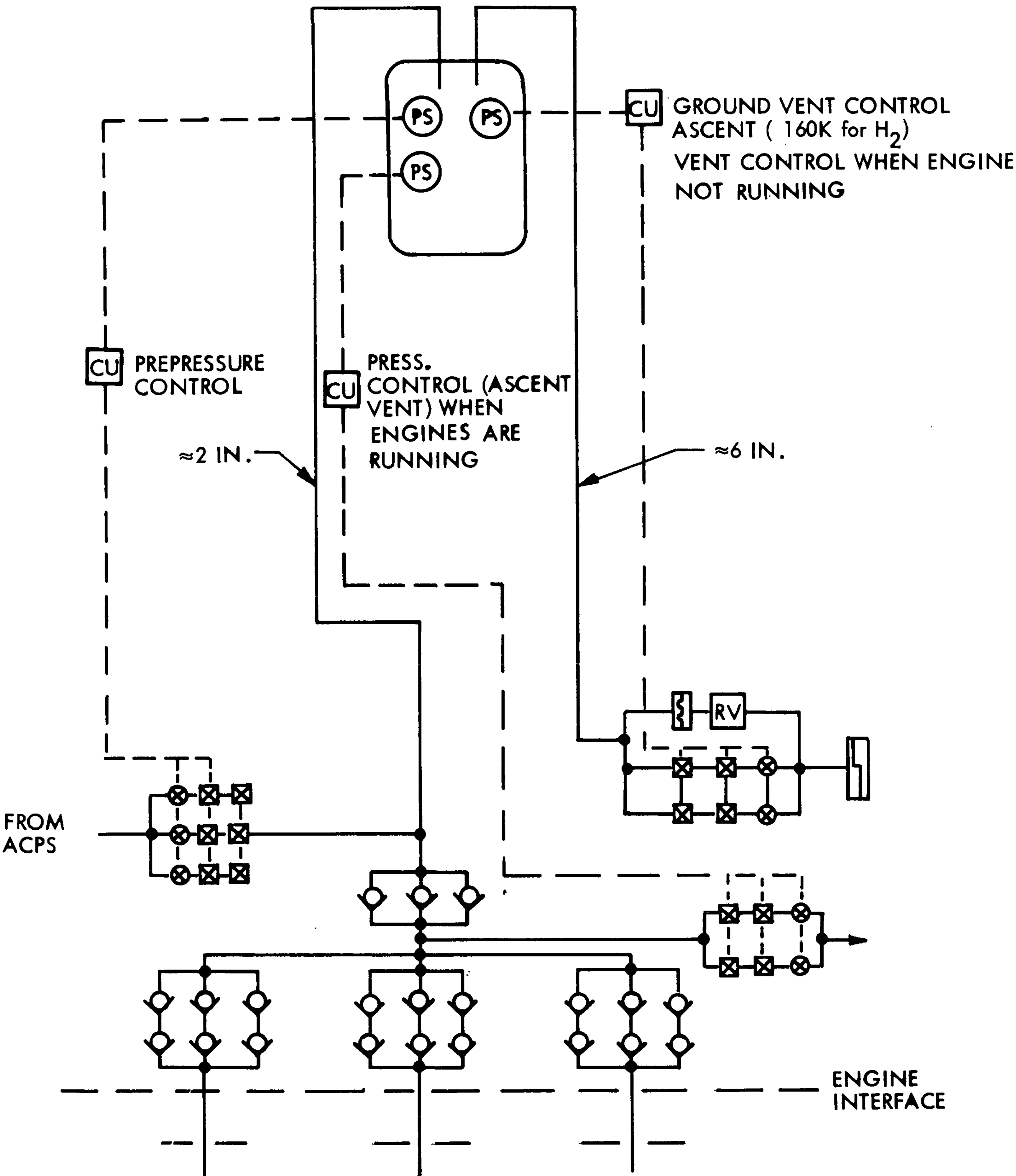

Fig. 9.2-18 Separate Pressurization and Vent Lines

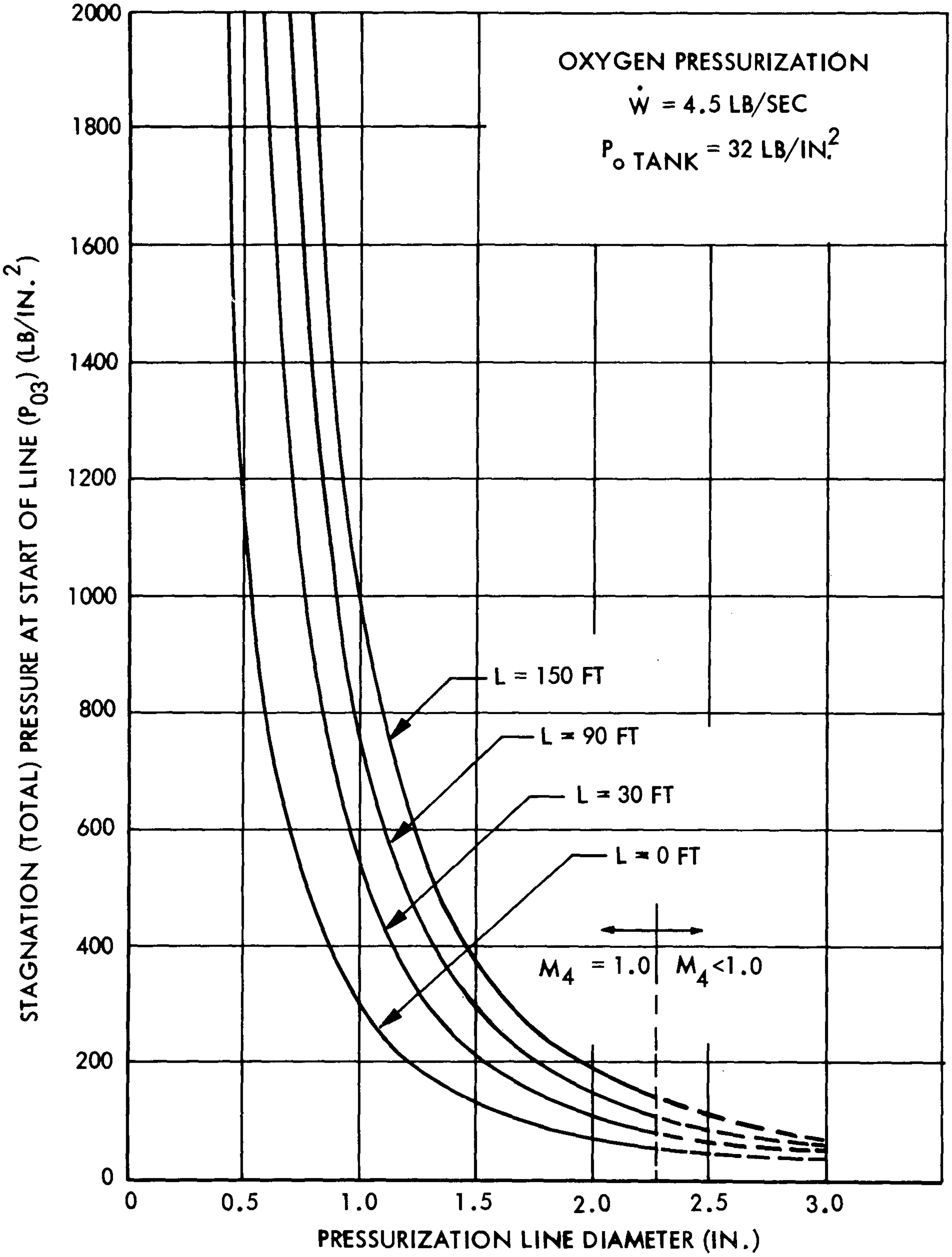

Fig. 9.2-19 Geometric Effects on Line Inlet Pressure – Oxygen

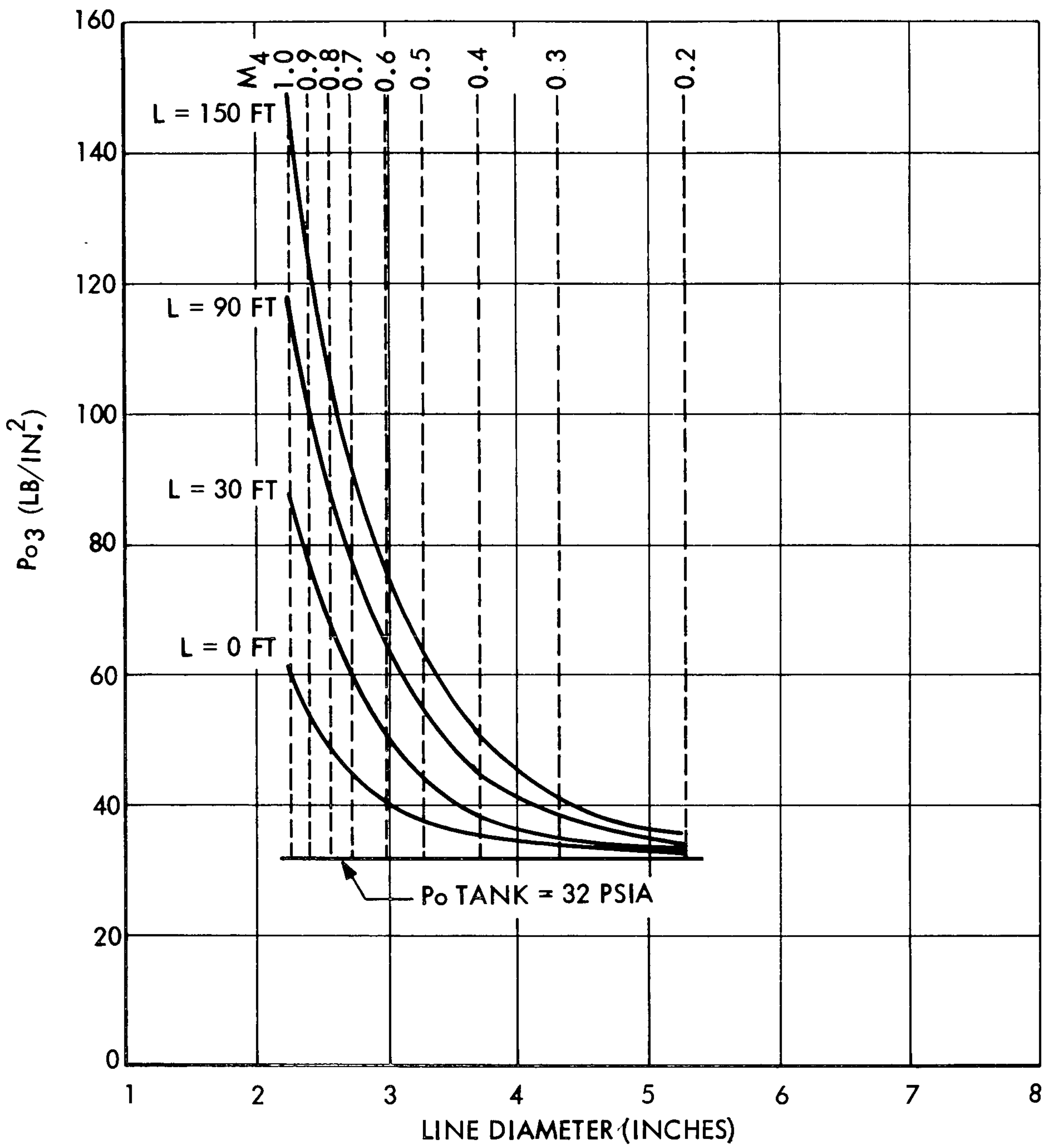

Fig. 9.2-20 Geometric Effects on Line Inlet Pressure – Oxygen

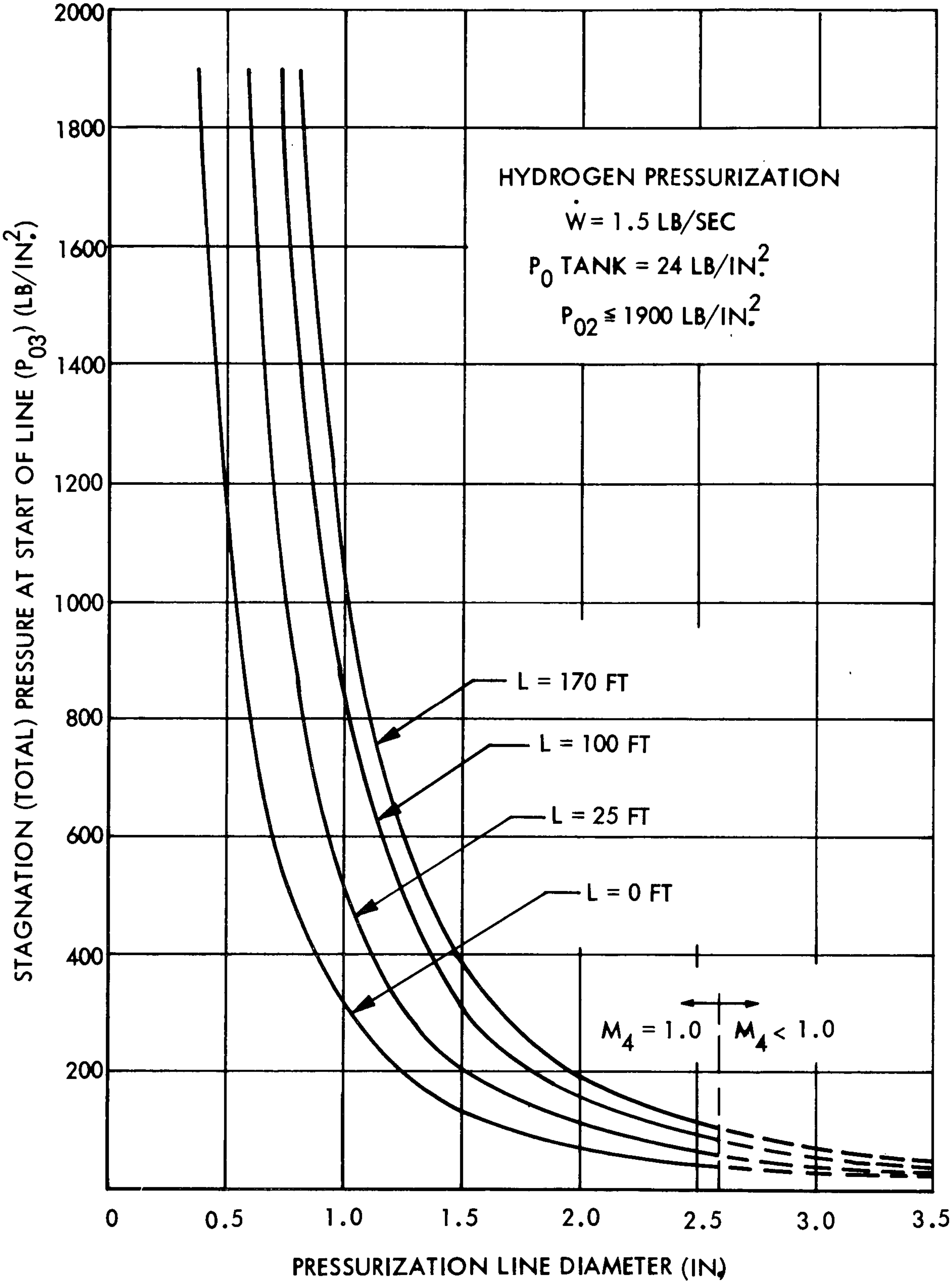

Fig. 9.2-21 Geometric Effects on Line Inlet Pressure – Hydrogen

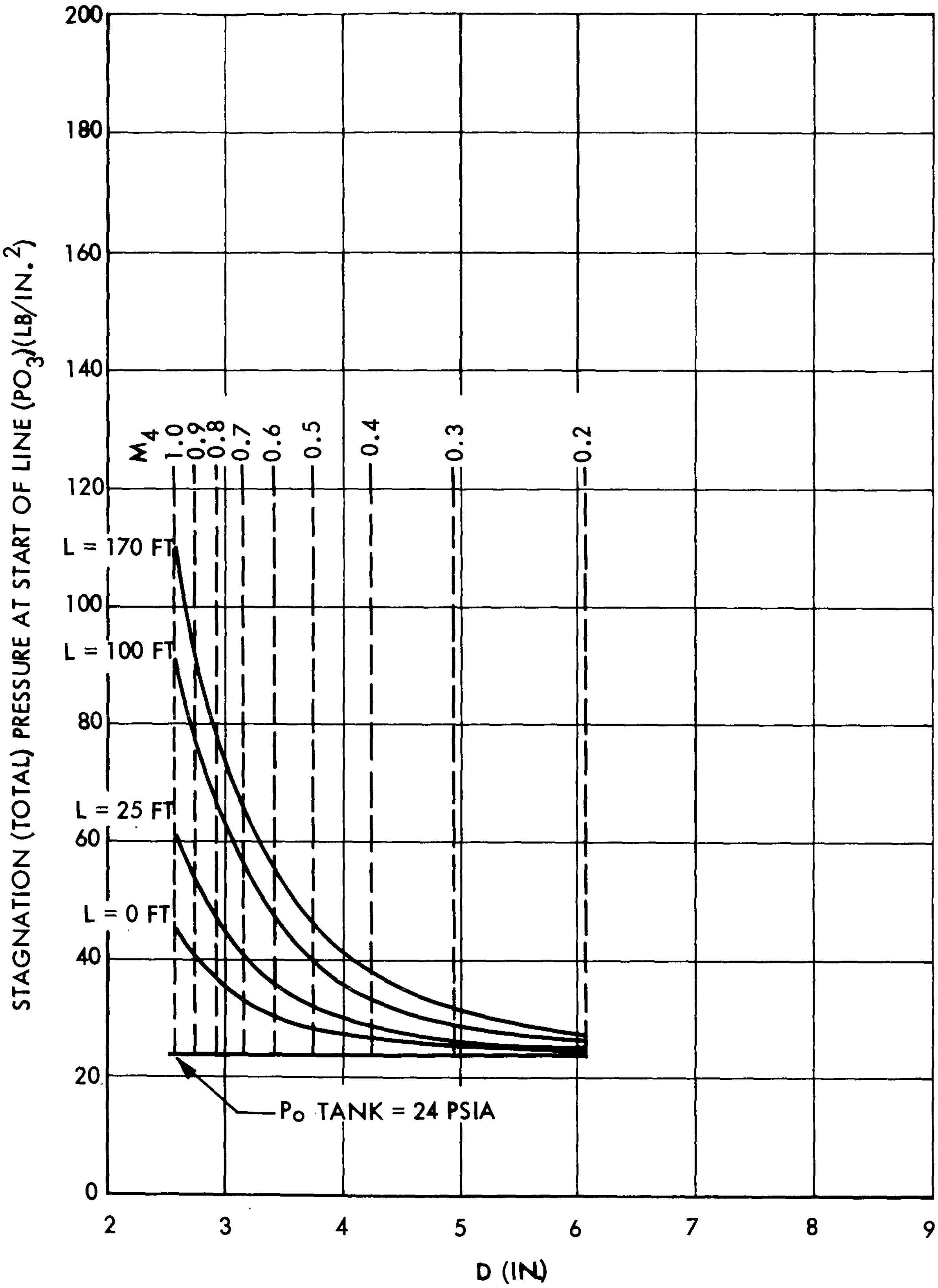

Fig. 9.2-22 Geometric Effect on Line Inlet Pressure – Hydrogen

During the fast-fill operation, the gas temperature can vary from ambient temperature down to saturated-vapor temperatures. The gas-flowrates will be greatest (thus the largest target pressure drop in the vent line will occur) during the fast-fill operation.

Figure 9.2-23 shows the pressure drop per unit line length as a function of vent-gas temperature for both the hydrogen and oxygen for various line diameters. The fast-fill volume-flowrates of liquid hydrogen and liquid oxygen were held constant at 11,790 gal/min for hydrogen and 3,350 gal/min for oxygen. The vent-gas mass-flowrate will be a function of temperature, since the density is greatest at these temperatures and the volume-flowrates are constant. The maximum pressure drop occurs at the saturated-vapor temperature for all line sizes considered.

Then, parametric pressure drop versus line length curves were generated for various line diameters for vent gas temperatures corresponding to saturated vapor, because this condition represents the maximum pressure drops expected. These curves, shown in Fig. 9.2-24, are based on the fast-fill rates given above. For different liquid-fill rates, the corresponding pressure drops will be proportional to the square of the flowrate (volume-flowrate).

Pressure drop curves were generated then for the valves located in the vent lines for various line diameters. These pressure drops were based on using butterfly-type valves with a flow-element-area-to-line-area ratio of 0.85 and a flow coefficient (c) of 0.65. The curves shown in Fig. 9.2-25 use the same fast-fill rates given above and two valve-inlet pressures (16 psia and 25 psia). Again, the pressure drops are proportional to the square of the fill rate.

The flowrates associated with steady-state boiloff then were determined as a function of the tank-area-to-foam-insulation-thickness ratio (Fig. 9.2-26). Also noted in this figure is the mass-flowrates associated with the nominal fast-fill rates. This curve shows that for O_2, if the tank-area-to-insulation-thickness is greater than about 10,600 ft^2/in., then the boiloff-flowrate

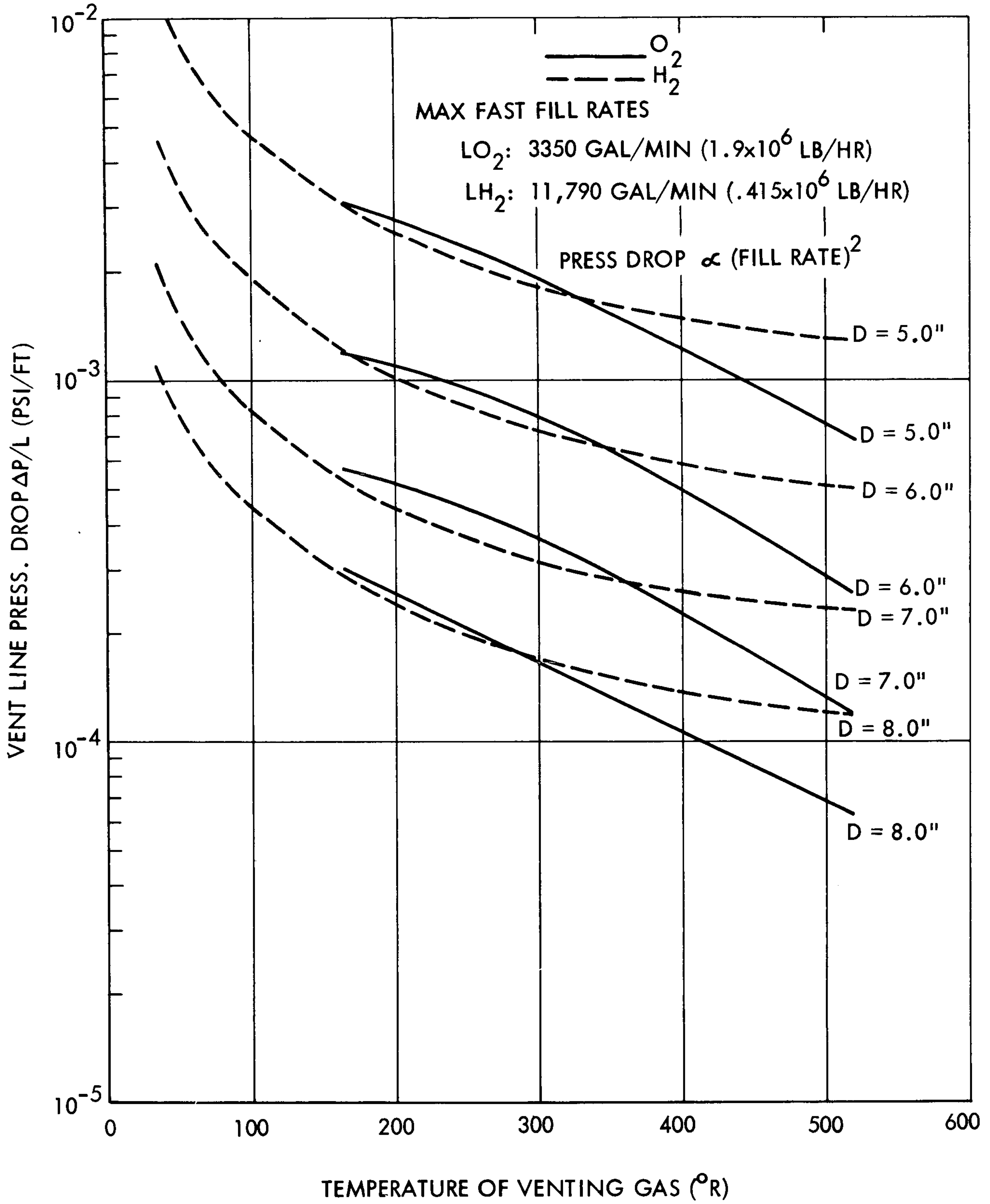

Fig. 9.2-23 **Effect of Temperature on Vented Gas Pressure Drop**

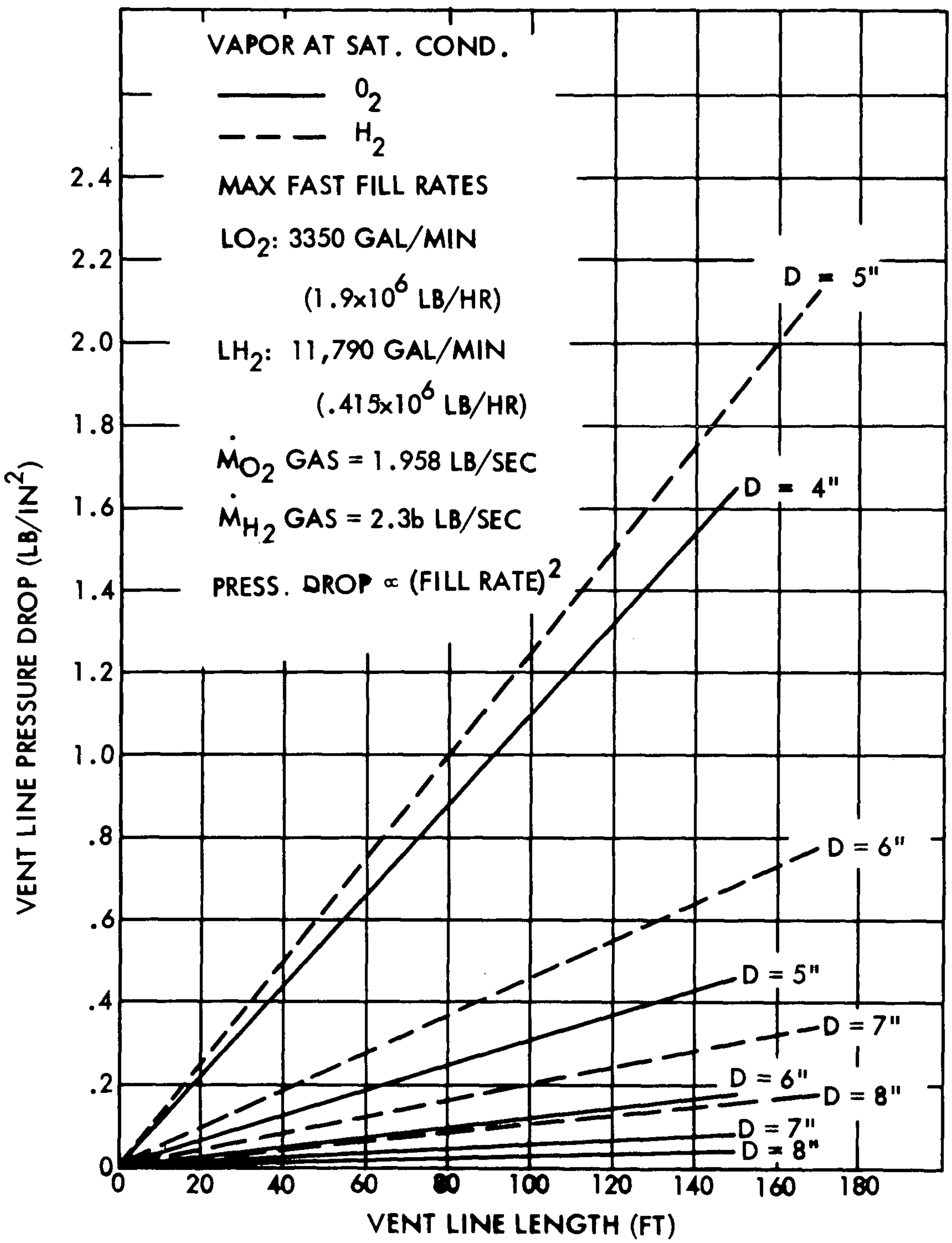

Fig. 9.2-24 Vent Line Pressure Losses

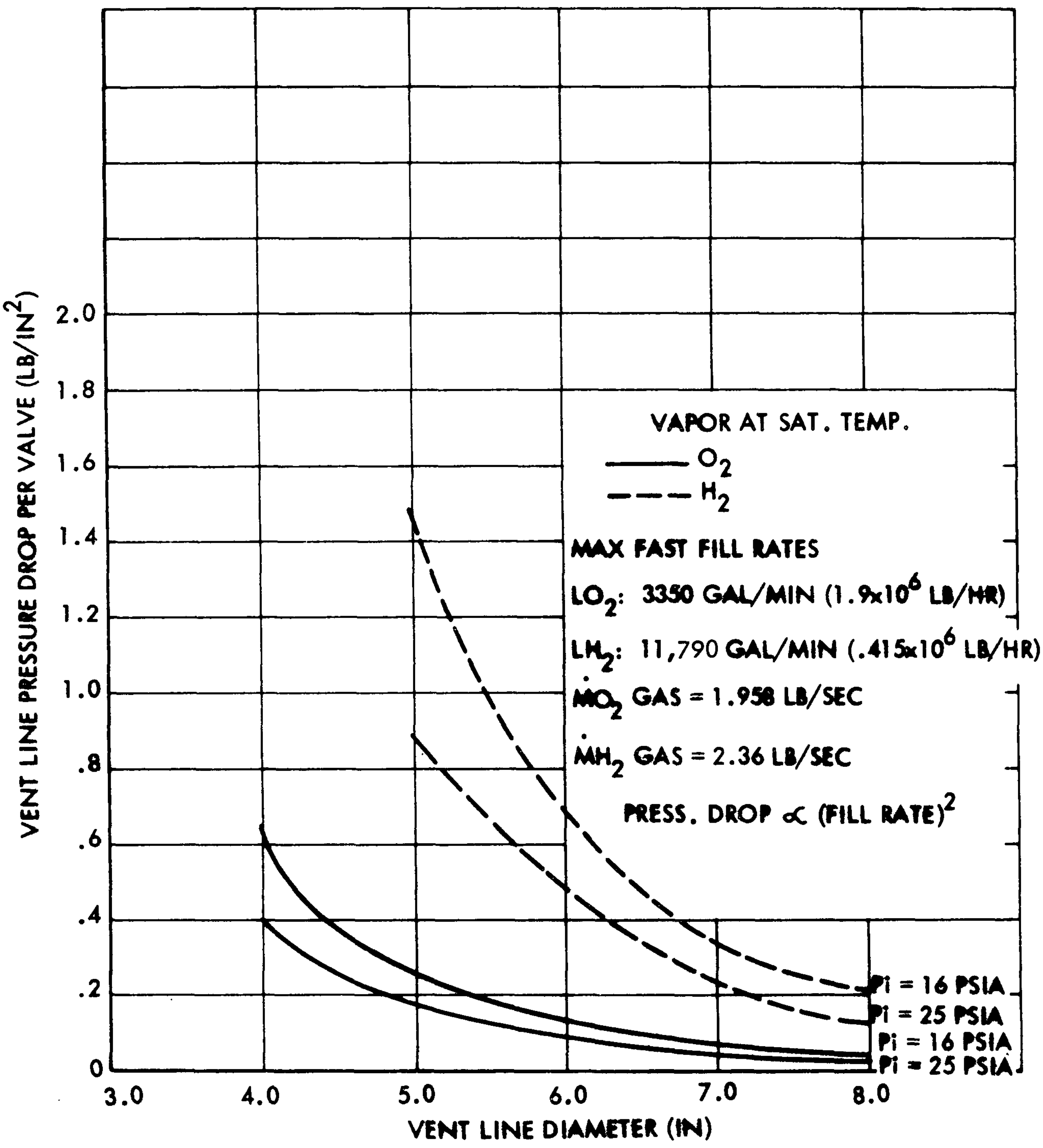

Fig. 9.2-25 Vent Line Pressure Losses

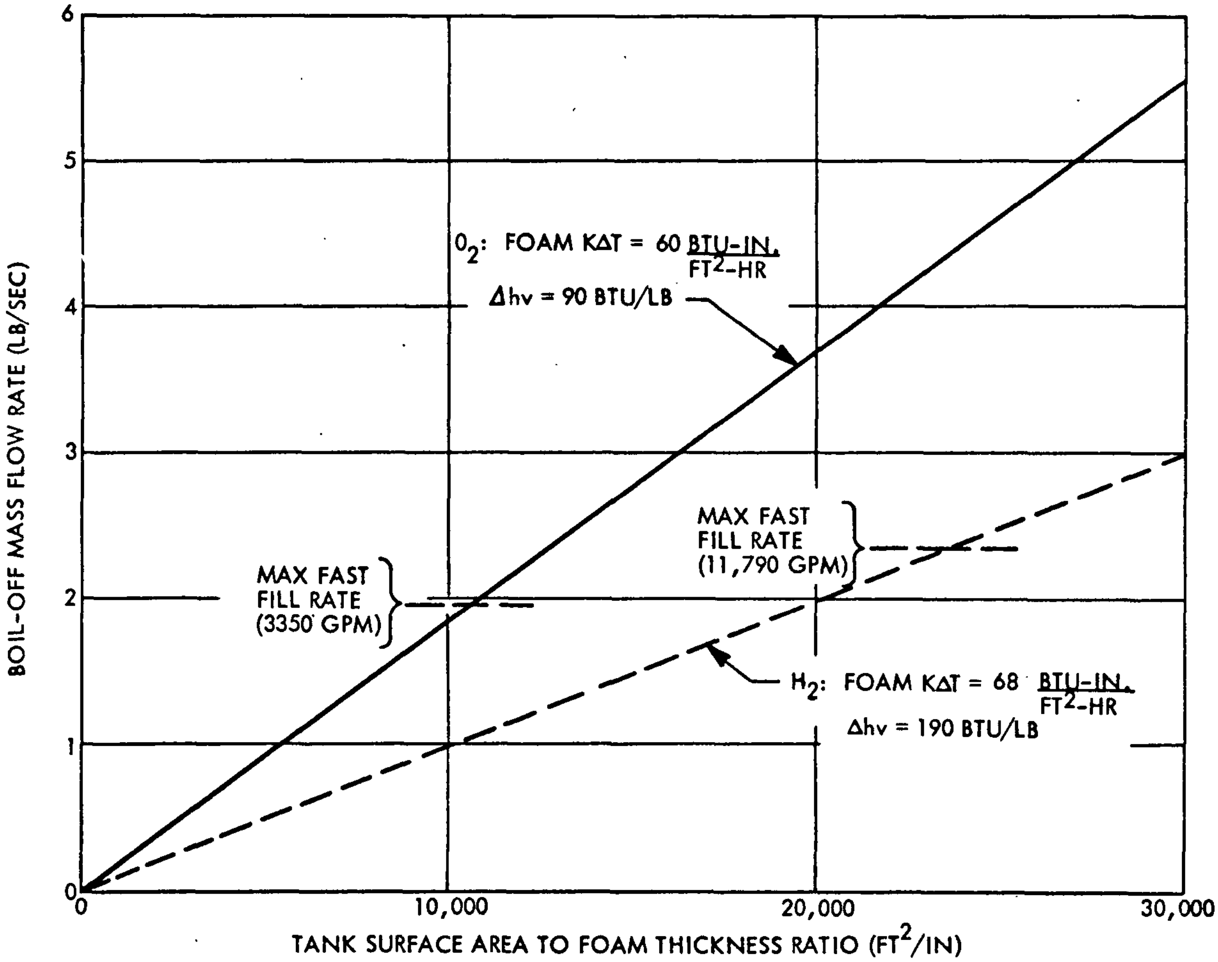

Fig. 9.2-26 Steady-State Boiloff Rates

is greater than during fast fill, and it is the latter mode that becomes the design factor for the vent lines. The comparable tank-area-to-insulation-thickness ratio for the H_2 tank is about 23,500 ft^2/in. Also considered in the boiloff rate analyses was the case for an internally mounted uninsulated O_2 tank surrounded by a nitrogen blank. The associated O_2 boiloff rates, as a function of tank area, is given in Fig. 9.2-27. This curve shows that for a tank area greater than about 600 ft^2, the boiloff rate will exceed the nominal fast-fill flowrate.

9.2.2.3.3. Conclusions Regarding Common Pressurization and Vent Lines. Dependent upon the tank design, area, and other factors, the required vent lines are generally 6 inches in diameter or greater. As seen from examination of the pressurization curves, a 6-in. line results in low-pressure drops, and relatively low-pressure lines could be used with the constant-bleed flowrate from the engine provided that the venting was fail-operational, fail-safe. Therefore, a common pressurization vent line is possible.

9.2.2.4. OIPS Feedline Temperature Control and Insulation Evaluations.

9.2.2.4.1. Forced Circulation in the Feedlines. A study was performed to determine the sensitivities to insulation thickness and flowrates in the OIPS feedlines. The parameters considered included: feedline lengths (typical of the North American Rockwell and McDonnell-Douglas vehicle configuration); feedline diameters (12, 14, and 16 in.); feedline insulation-type and thickness (polyurethane foam at 1/2- and 1-in. thicknesses); and circulation flowrate.

Major sources of heat leaks into the feedline system included those: through the feedline insulation, from the engine, through the recirculation line insulation, and from the circulation pump due to pump inefficiency.

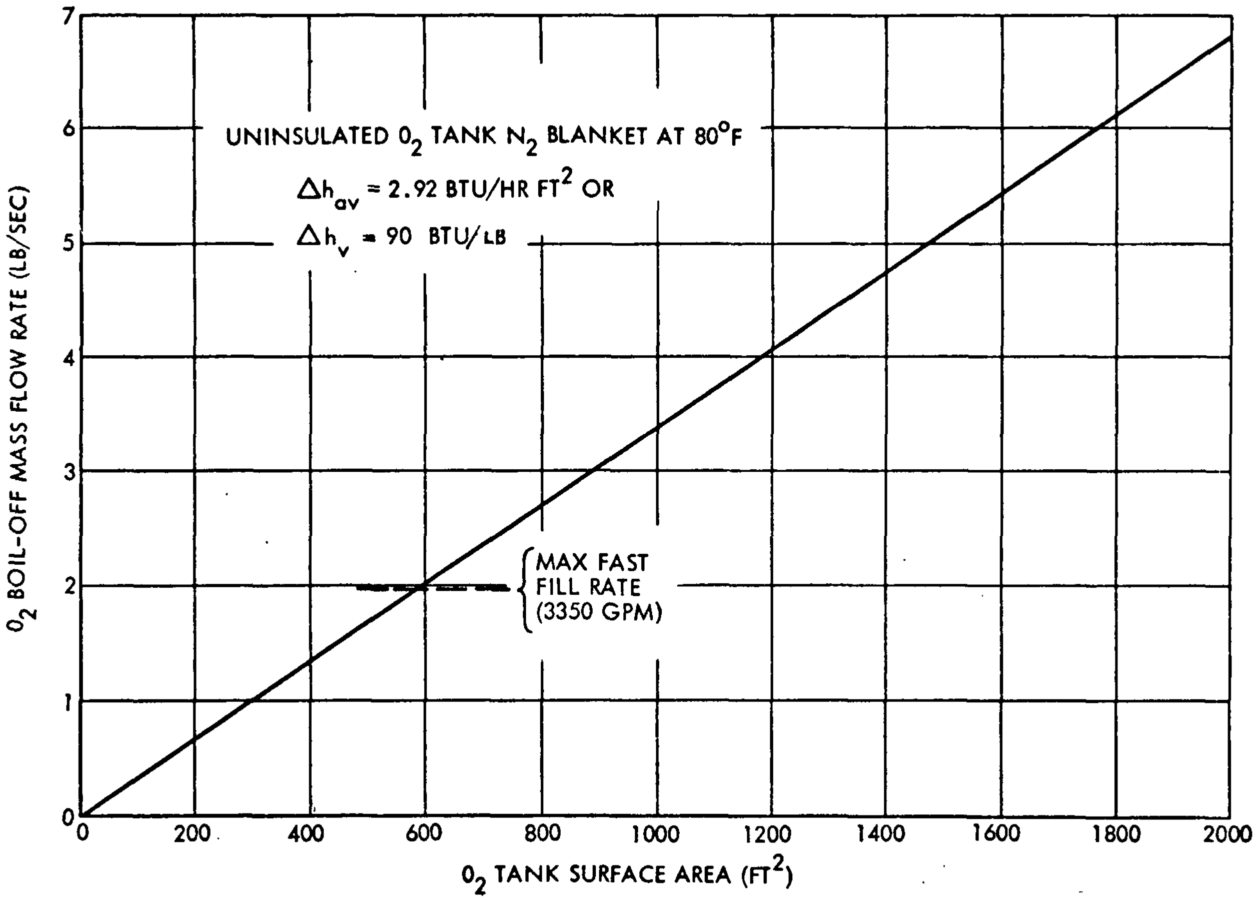

Fig. 9.2-27 Steady-State Boiloff Rates

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Total temperature-rise sensitivity to various feedline diameters, foam-insulation thicknesses, and vehicle configuration (line lengths) are shown in Figs. 9.2-28 through 9.2-31 as a function of circulation flowrate per engine/line loop for both LH_2 and LO_2. The feed system was split into two loops - each loop consisting of one engine, the feedline for that engine, the circulation line for that engine, a pump for that engine, and one half of the feed interconnect line.

For this study, the heat leak from each engine turbopump assembly was assumed constant and equal to 10 Btu/sec. The circulation-line diameter and insulation were considered constant and equal to 2 in. (diameter) and 0.214 in. (NRC-2 insulation thickness), respectively, which result in a heat leak per unit length of 4.04 Btu/hr-ft.

The total temperature rise shown in Figs. 9.2-28 through 9.2-31 includes the temperature rise through a feedline, across one engine, through a circulation line, and across a circulation pump back to the storage tank. Figures 9.2-32 through 9.2.35 present the temperature rise through a feedline for the same parameters, whereas Figs. 9.2-36 and 9.2-37 show the temperature rise across the engine turbopumps assemblies. These two heat sources make up the major portion of the total temperature rise, with small temperature rises occurring through the circulation line and pump.

From Figs. 9.2-28 through 9.2-37 it was determined that the insulation thicknesses and line sizes do not have a pronounced effect. Since the total temperature rise for some of the configurations was greater than $1^{\circ}R$ for the flowrates considered (1-to-5 lb/sec for LH_2 and 6-to-14 lb/sec for LO_2), additional analyses were performed at increased flowrates such that the total temperature rise would be less than $1^{\circ}R$. For these analyses only, the 14-in. feedline diameter was considered, because at the higher flowrates, the sensitivity to feedline diameter is small. In addition to the two foam-insulation thicknesses considered before, multilayer NRC-2 was included at thicknesses of 1/2 and 1 in. The 1/2-in. NRC-2 thickness reduced the heat leak through the feedline to such a small amount that the difference

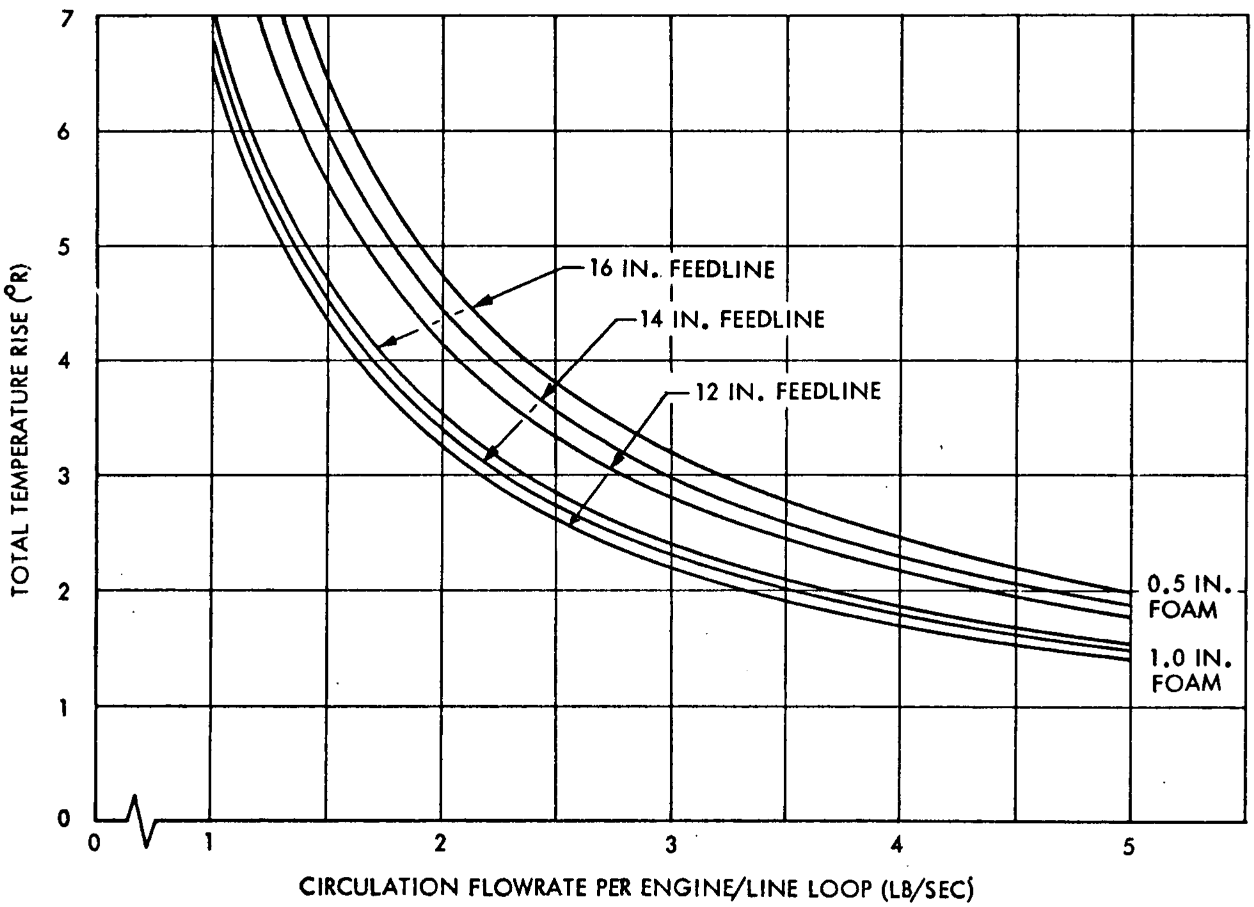

Fig. 9.2-28 Effect of Circulation Flowrate on Temperature Rise - OIPS NAR LH_2 System (L ≈ 76 ft)

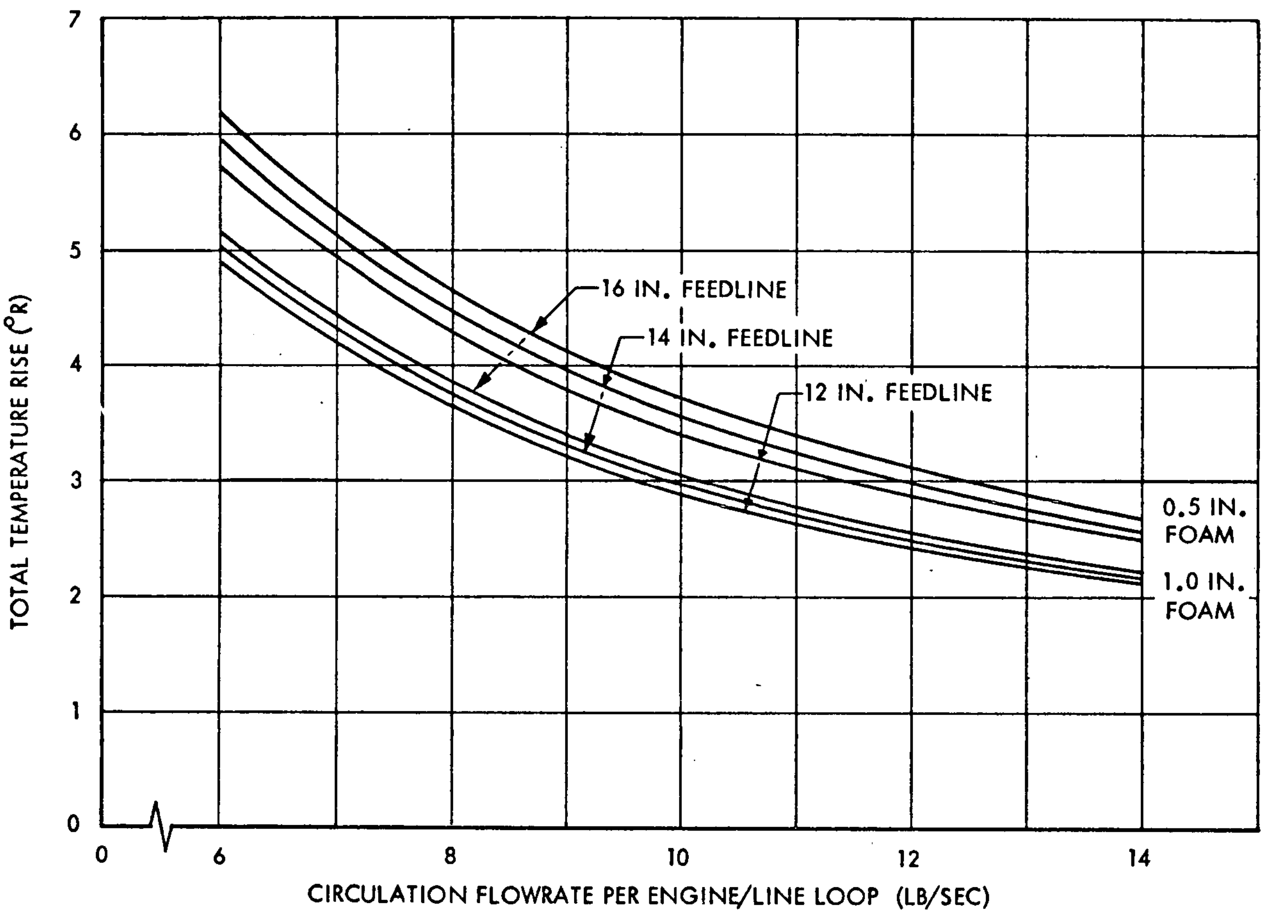

Fig. 9.2-29 Effect of Circulation Flowrate on Temperature Rise - OIPS NAR LO_2 System ($L \approx 45$ ft)

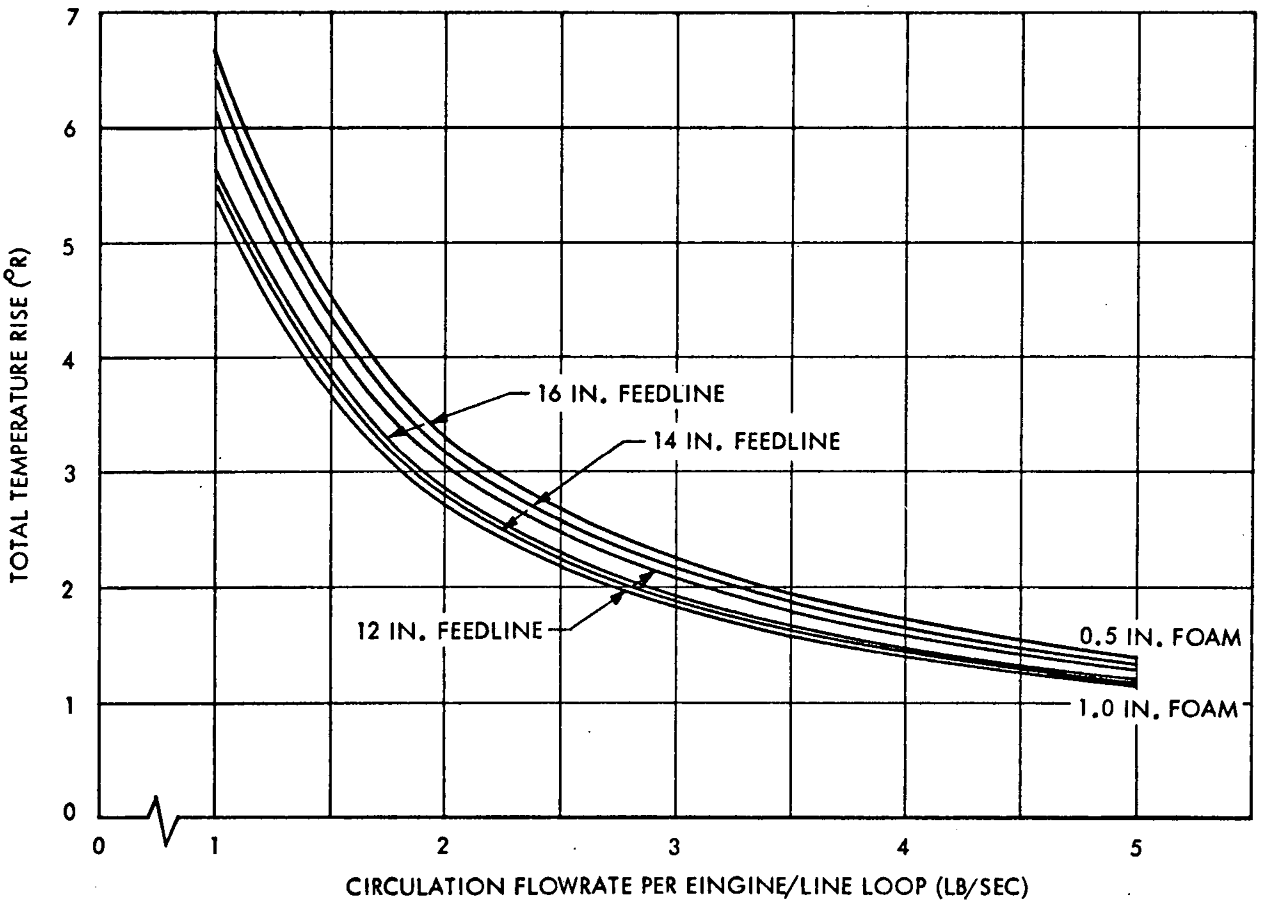

Fig. 9.2-30 Effect of Circulation Flowrate on Temperature Rise - OIPS MDC LH_2 System ($L \approx 31$ ft)

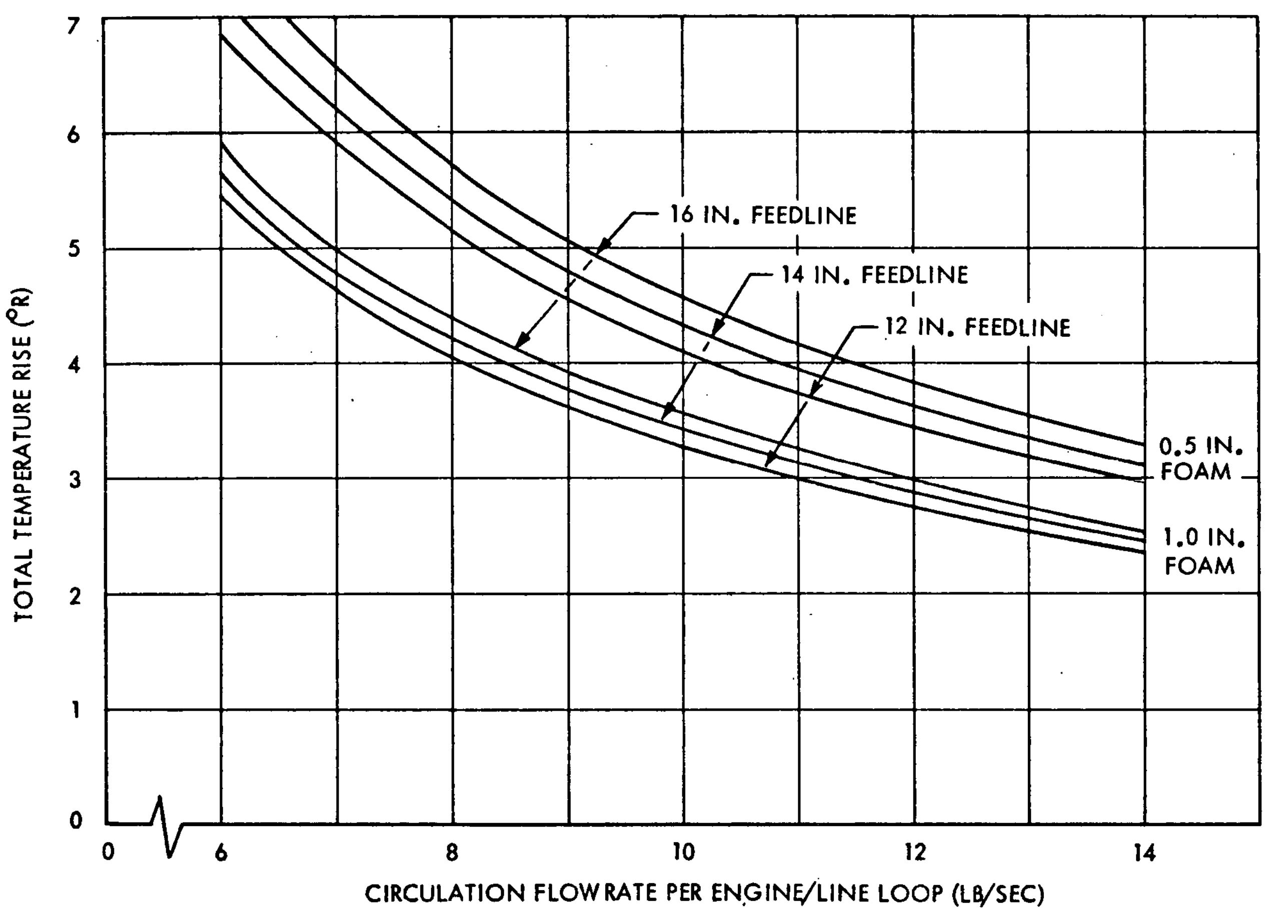

Fig. 9.2-31 Effect of Circulation Flowrate on Temperature Rise - OIPS MDC LO_2 System ($L \approx 75$ ft)

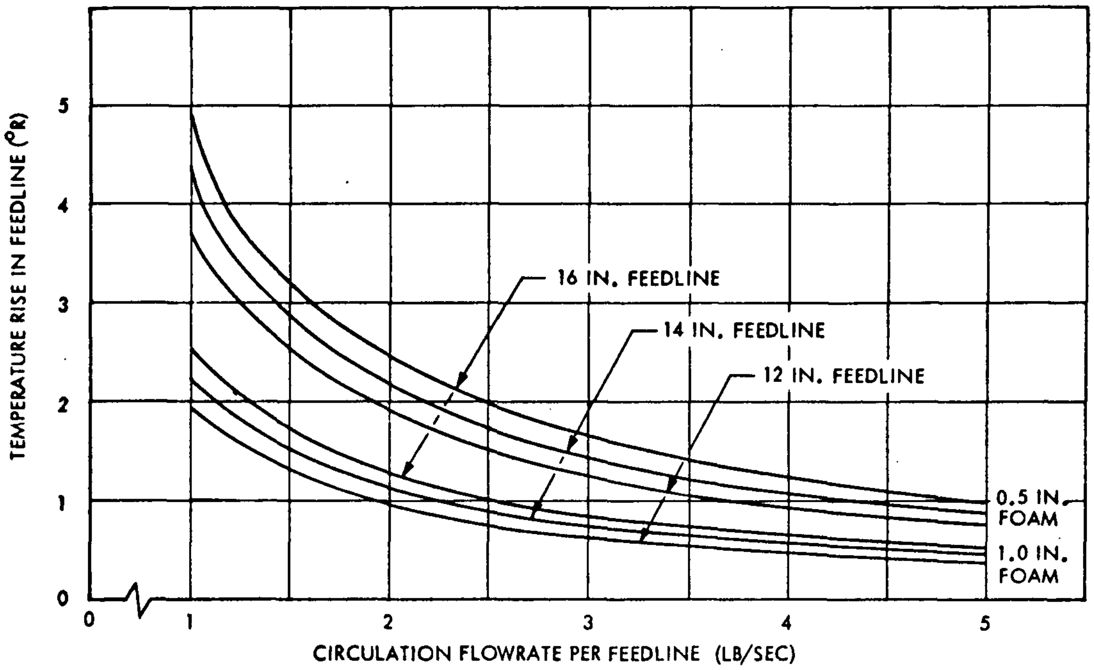

Fig. 9.2-32 Temperature Rise in NAR LH_2 Feedline ($L \approx 26$ Ft)

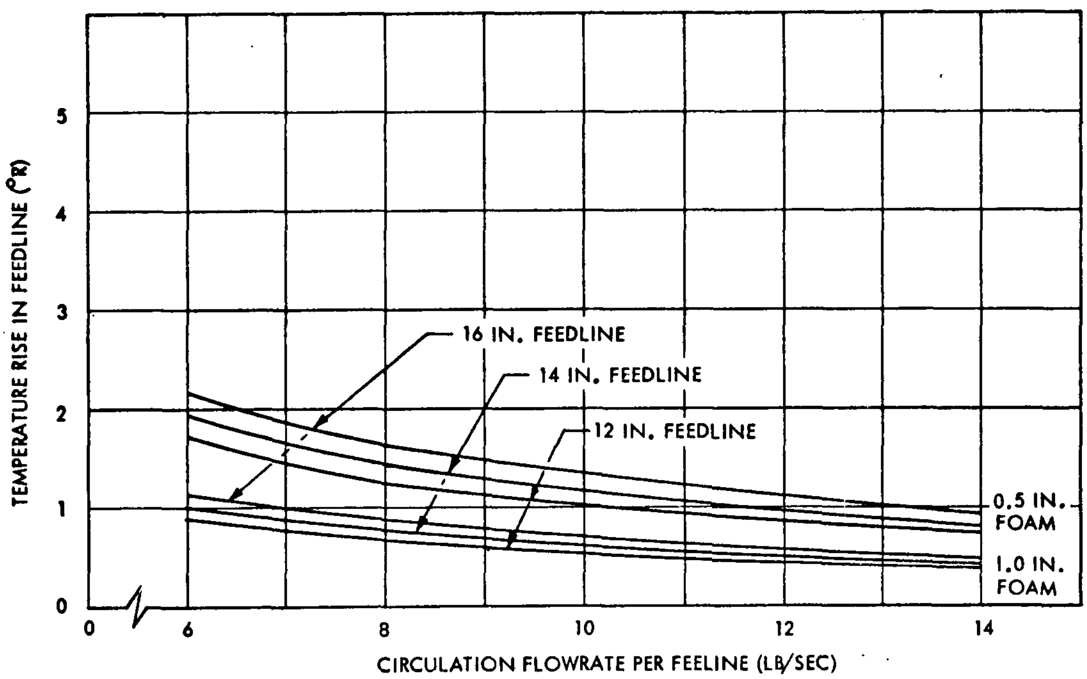

Fig. 9.2-33 Temperature Rise in NAR LO_2 Feedline ($L \approx 45$ Ft)

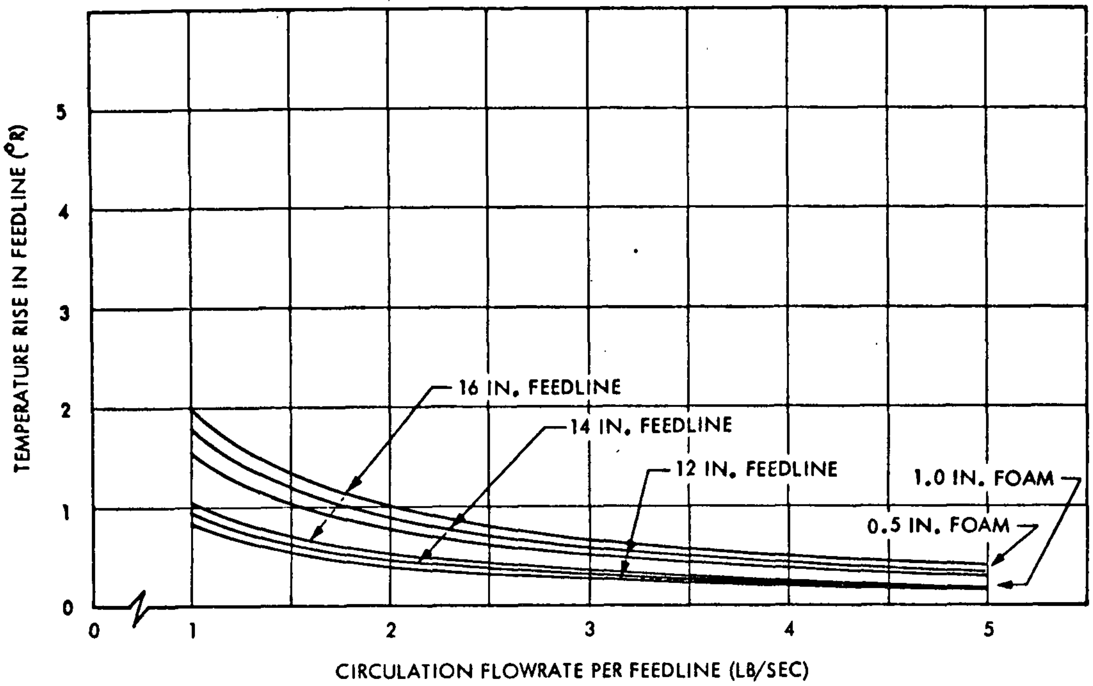

Fig. 9.2-34 Temperature Rise in MDC LH_2 Feedline ($L \approx 31$ Ft)

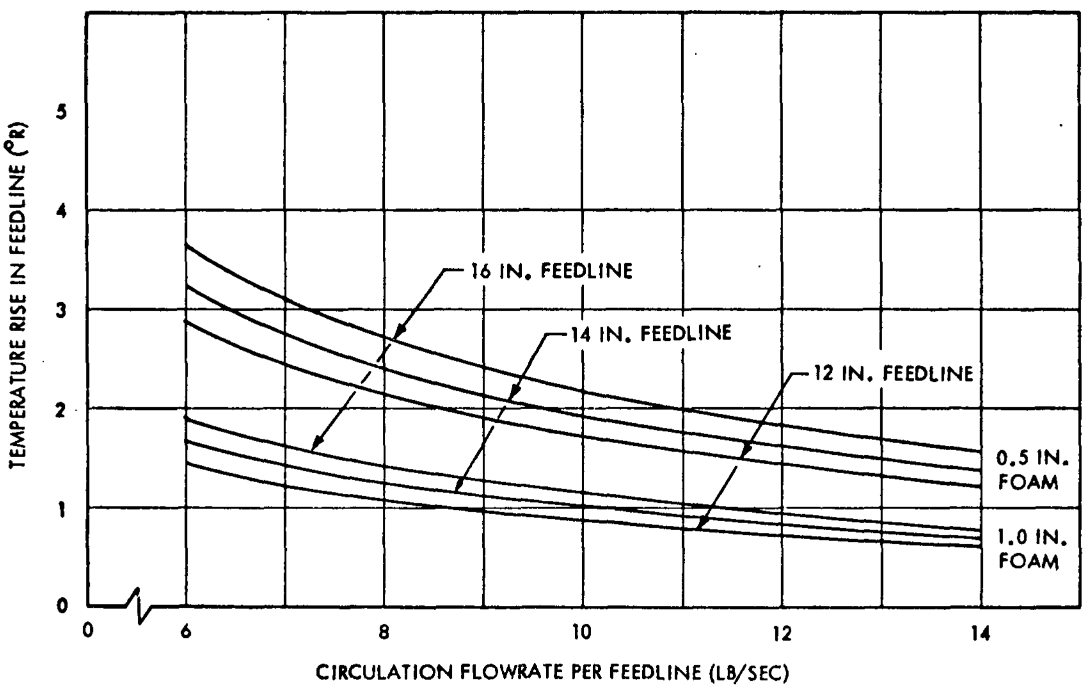

Fig. 9.2-35 Temperature Rise in MDC LO_2 Feedline ($L \approx 75$ Ft)

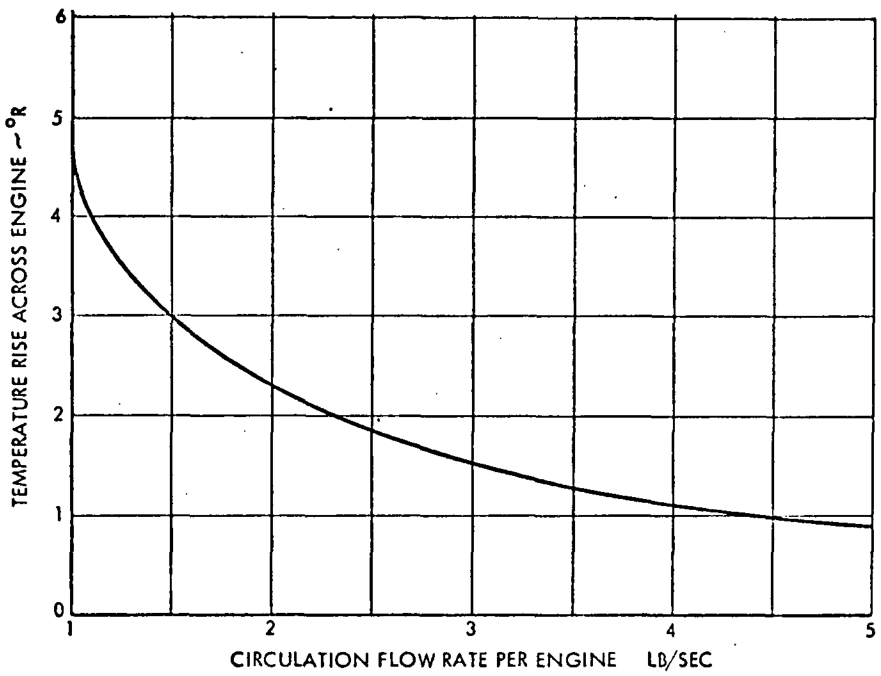

Fig. 9.2-36 Temperature Rise Across Engine - LH_2 Turbopump ($\dot{Q}$ = 10 Btu/Sec)

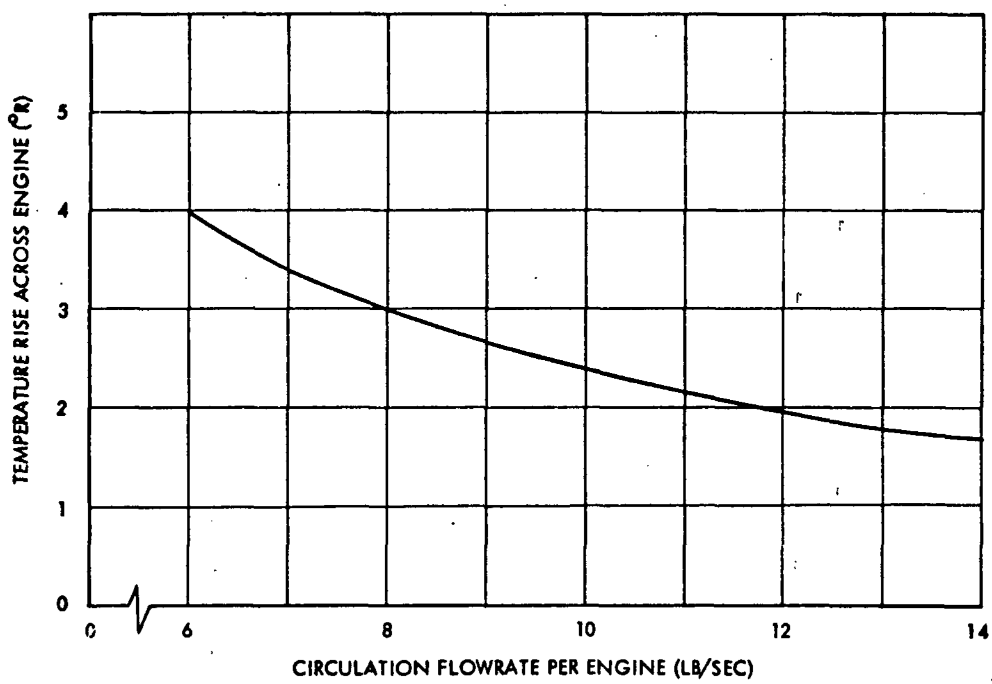

Fig. 9.2-37 Temperature Rise Across Engine - LO_2 Turbopump ($\dot{Q}$ = 10 Btu/Sec)

in temperature rise for 1/2 or 1 in. of NRC-2 is negligible. Also, for the liquid oxygen, the lines were examined with no insulation.

The total temperature rise sensitivity to the various insulation types and thicknesses and vehicle configuration are shown in Figs. 9.2-38 through 9.2-41 for circulation flowrate of 1-to-10 lb/sec for the LH_2 systems and 5-to-50 lb/sec for the LO_2 systems.

Free or natural convection effects were neglected in this study, since they are negligible for the larger forced flowrates. However, these effects could be significant at the lower flowrates.

Pressure drops in the system during circulation arise primarily in the circulation-line friction drop and the engine recirculation valve. The pressure drop in the feedlines for these relatively low flowrates were neglected. With these pressure drops, the required pump power is shown in Figs. 9.2-42 and 9.2-43 as a function of vehicle configuration and flowrate. These curves were drawn for a constant recirculation valve area and, thus, become quite large at the higher flowrates due to the large pressure drop across these valves. The power requirements, shown in Figs. 9.2-42 and 9.2-43 can be reduced by increasing the engine recirculation-valve size, which would result if the valve sizes were optimized for each flowrate. It is apparent from these curves that the circulation would require approximately 5 hp for both the liquid-hydrogen and the liquid-oxygen pumps, if the lines are insulated. If the oxygen lines are not insulated, the power required for circulation to keep the temperature rise below $1^\circ R$ would be very high.

9.2.2.4.2. Natural Convection Cooling of Liquid-Oxygen Feedlines. Thermal and fluid dynamic analyses were conducted to determine the behavior of propellants contained in the feedlines of the McDonnell-Douglas Phase B orbit injection tanks. These were chosen because the design resulted in long LO_2 feedlines.

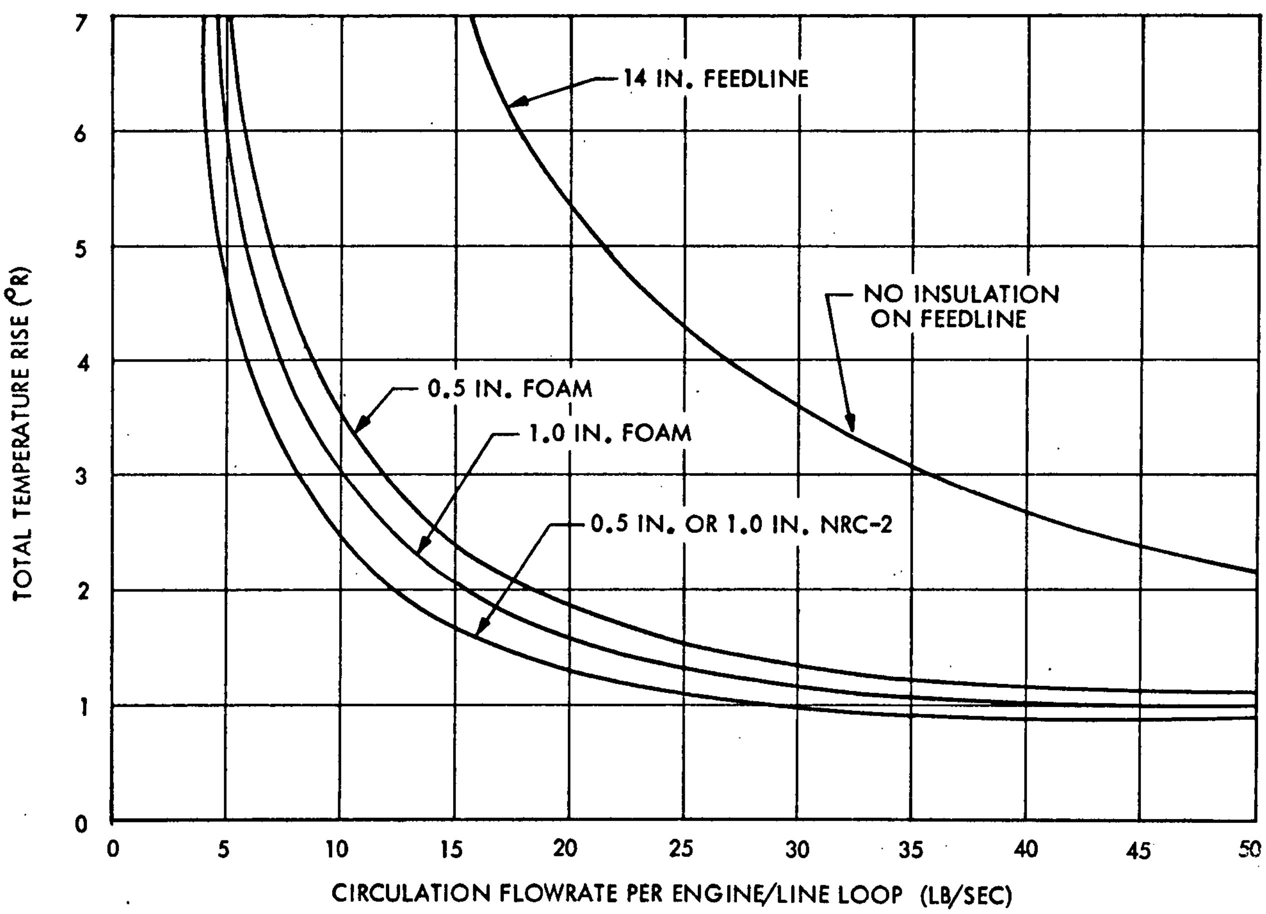

Fig. 9.2-38 Effect of Circulation Flowrate on Temperature Rise OIPS NAR LH_2 System (L ≈ 76 ft), 14-in. Feedline

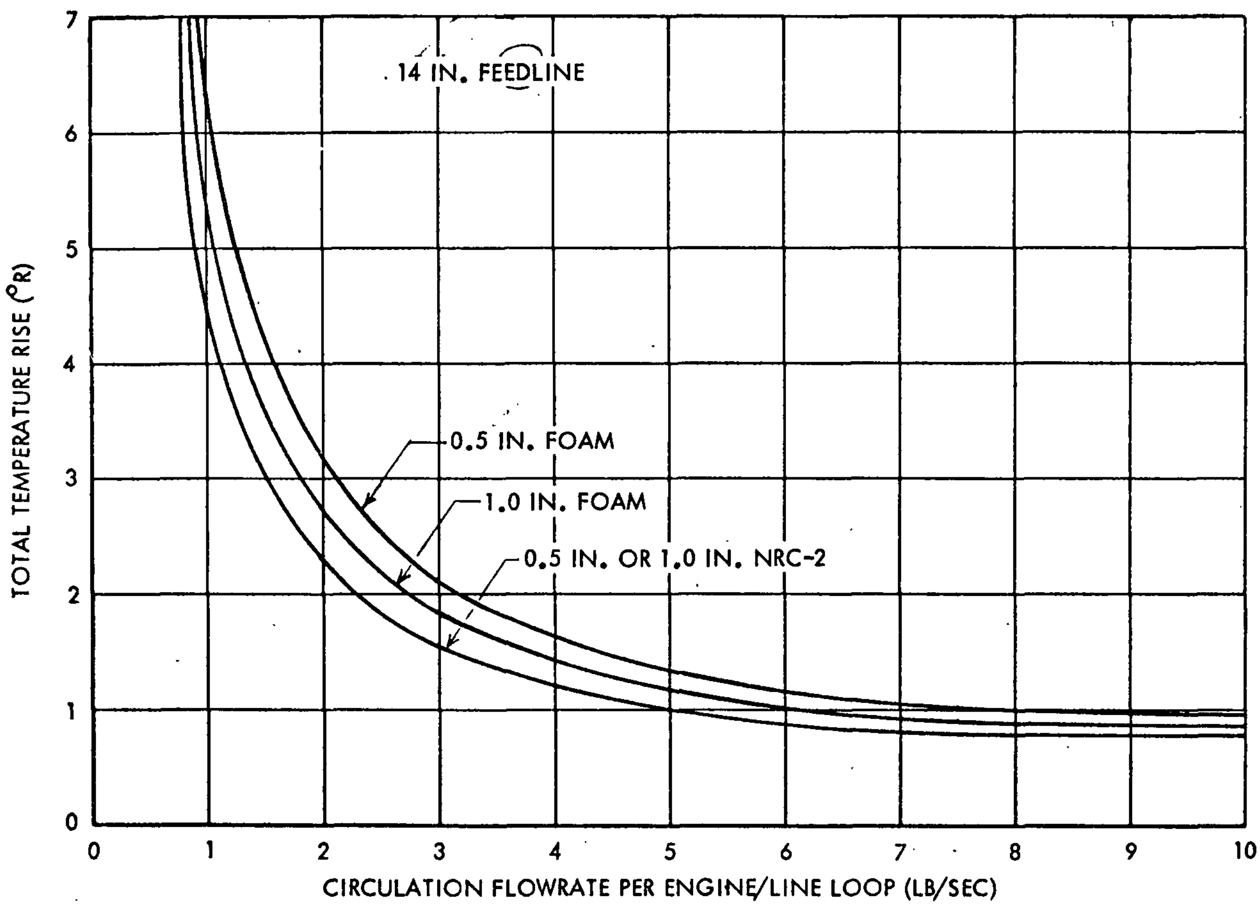

Fig. 9.2-39 OIPS Feedline Circulation Effect
NAR - LO_2 System (L = 45 Ft)

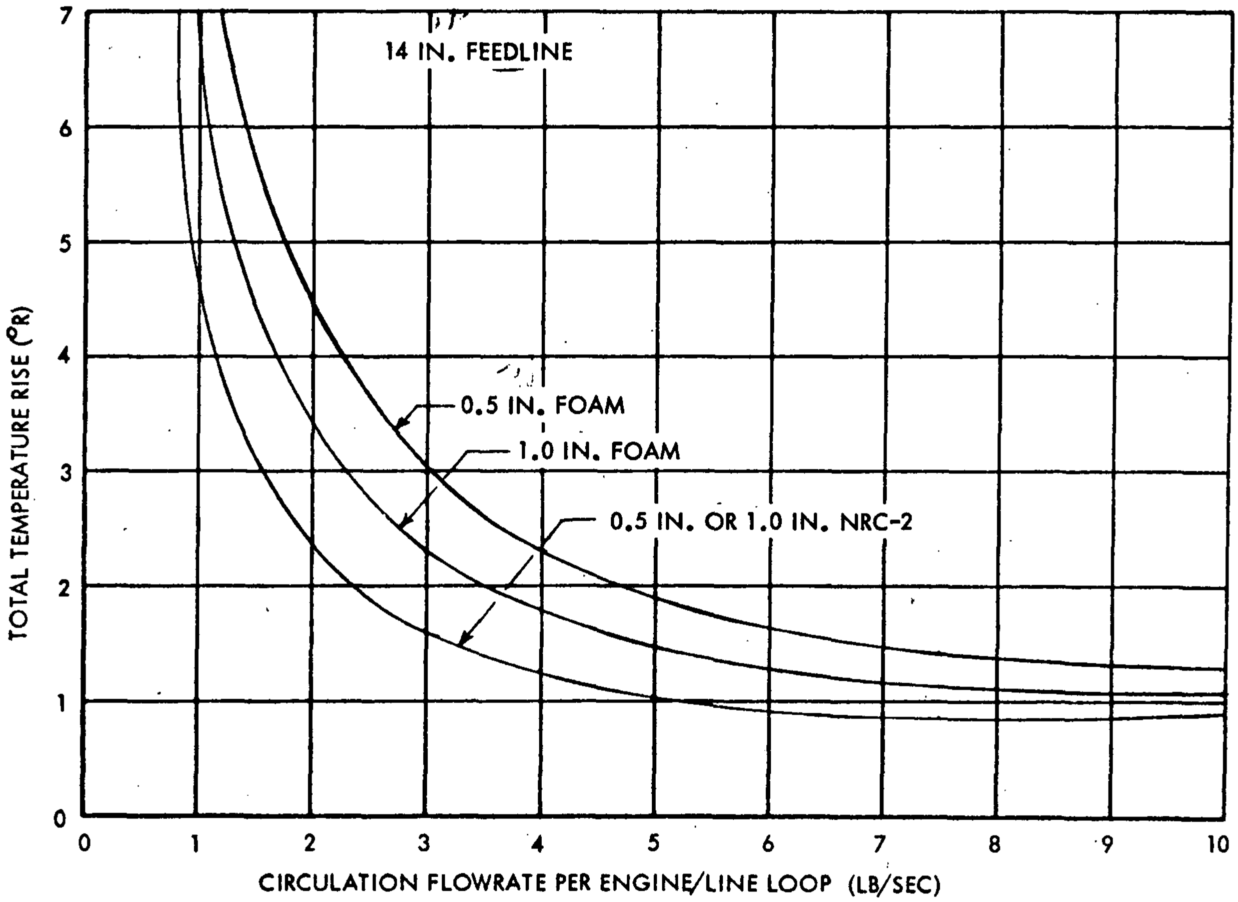

Fig. 9.2-40 OIPS Feedline Circulation Effect
MDC LH_2 System (L = 31 Ft)

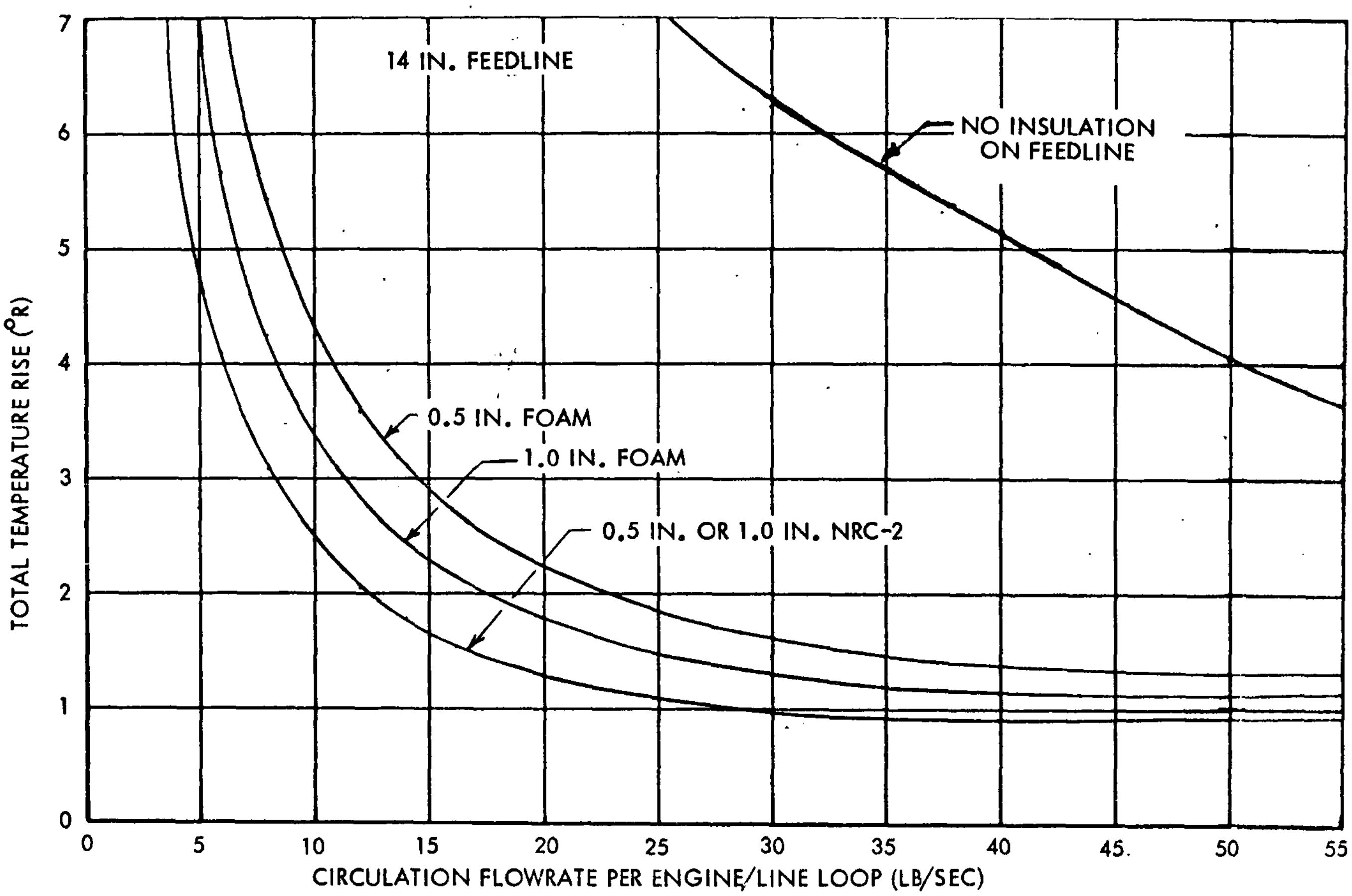

Fig. 9.2-41 OIPS Feedline Circulation Effect
MDC LO_2 System (L = 75 Ft)

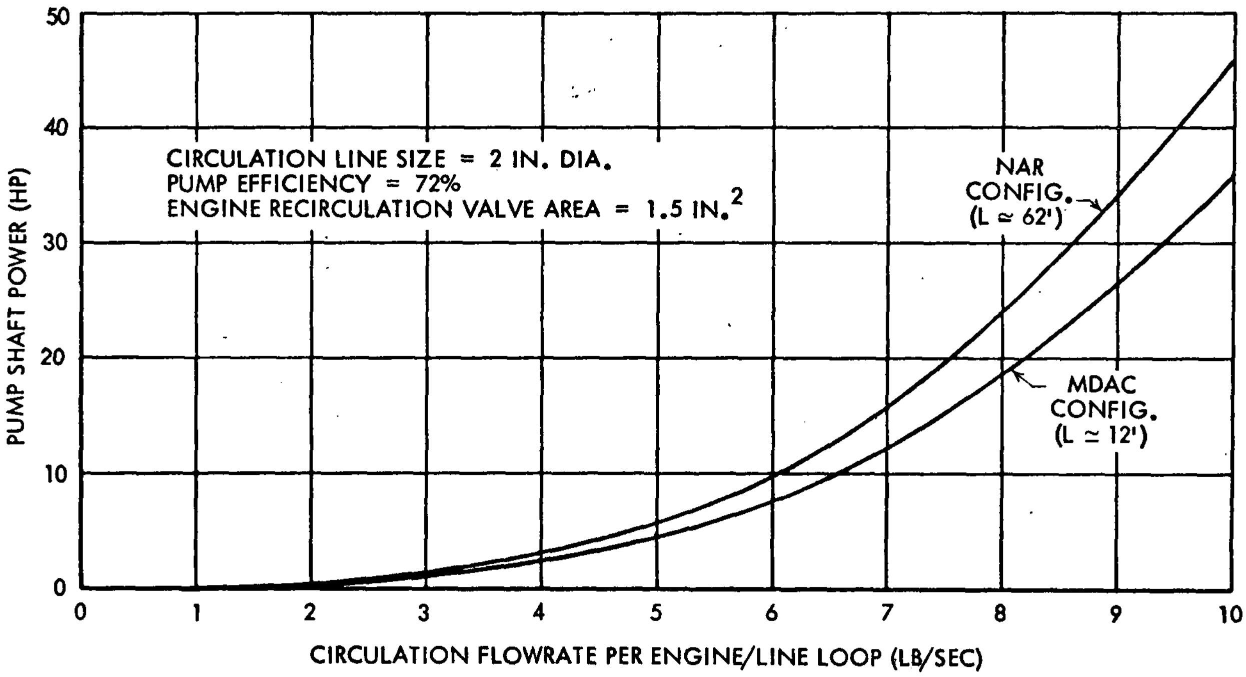

Fig. 9.2-42 Required Pump Shaft Horse Power for Circulation LH_2

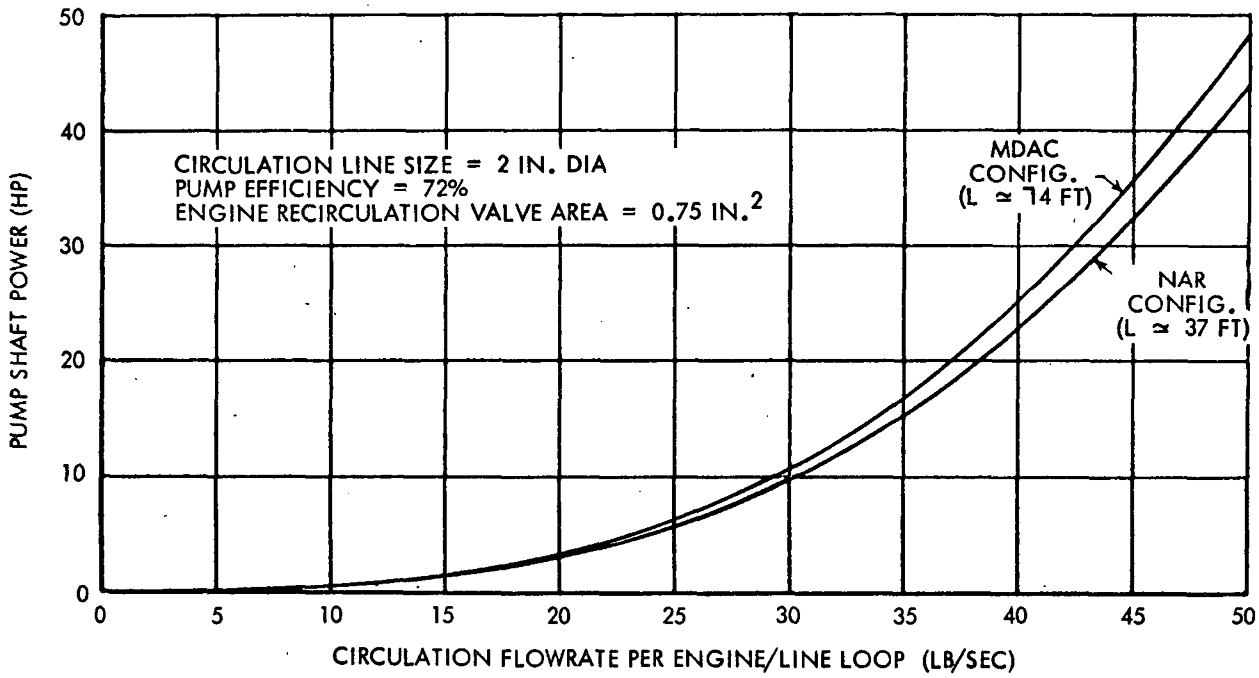

Fig. 9.2-43 Effect of Circulation Flowrate on Circulation Pump Shaft Requirements - OIPS LO_2 System

The Asymmetric Propellant Heating Computer Program was used to perform propellant heating, stratification, and pressurization computations. The liquid was treated in a stepwise-in-time manner and was stratified in horizontal layers. The boundary layer flow was considered to be turbulent. Adjacent layers were allowed to mix only when the time available was greater than the time required for a warmer layer to rise to the elevation of a cooler layer above. Also, it was necessary to adjust the boundary layer integration to limit the boundary layer thickness in the feedline to one-half the radius of the line.

The mission time period extended from the start of ground hold (180 sec before liftoff) through the boost phase (221 sec after liftoff). Fixed input data and initial conditions are shown in Table 9.2-1 while Table 9.2-2 presents the heating rates considered. Feedline heating rates and pump heating rates were organized so as to provide different heat rate levels. The ICD engines may be capable of producing heating rates of 10 Btu/sec. When this heating rate was used with the LH_2 lines, violent boiling and flashing were forecast, and it was not possible to perform convection-cooling analyses.

The propellant temperatures in the feedlines are shown in Figs. 9.2-44 through 9.2-48. High temperatures near the bottom were due to the high-heat input into the turbopumps. Although there was a substantial rise in liquid temperatures, at the higher heat fluxes a significant amount of energy was transported into the tank by the boundary layer flow and by mixing between layers. It is felt that the apparent steps in the temperature profiles of Figs 9.2-46 and 9.2-48 are due (1) to the limitations imposed upon mixing as a function of layer rise time and (2) to program operation with horizontal layers of finite thickness.

Table 9-2-1

FIXED INPUT DATA

	LO_2 TANK	LH_2 TANK
Propellant Loading (1), lb_m	226,510.0	68,800.0
Total Tank Volume (1), ft^3	3,323.0	16,704.0
Initial Ullage Volume (2), ft^3	146.0	1,146.0
Total Surface Area (1), ft^3	1,824.0	4,804.0
Feedline Diameter, in.	14.0	14.0
Feedline Length, ft	75.1	75.8
Pump Liquid Volume, ft^3	5.71	11.36
Additional Equivalent Feedline Length to Contain Liquid in Pumps, ft	5.34	10.62
Initial Propellant Temperature (3), ^oR	164.8	37.03
Operating Pressure, psia	25.0	40.0
Ground Hold Duration, sec	180.0	180.0

NOTES: (1) Includes feedline and turbopumps

(2) Initial ullage includes trapped vapor

(3) Initial condition at start of ground hold (saturated)

Table 9-2-2

HEATING RATES

Feedline Insulation	0.5 in. Foam	1.0 in. Foam	0.5 in. NRC-2
LO_2 Tank			
Wall Heat Flux, Btu/ft^2-sec	0.102	0.0288	0.00425
Feedline Heat Flux, Btu/ft-sec	0.1078	0.0555	0.00282
Pump Heat Input, Btu/sec	10.0	2.0	0.5
LH_2 Tank			
Wall Heat Flux, Btu/ft^2-sec		0.0131	0.00821
Feedline Heat Flux, Btu/ft-sec		0.0648	0.00318
Pump Heat Input, Btu/sec		3.0	1.0

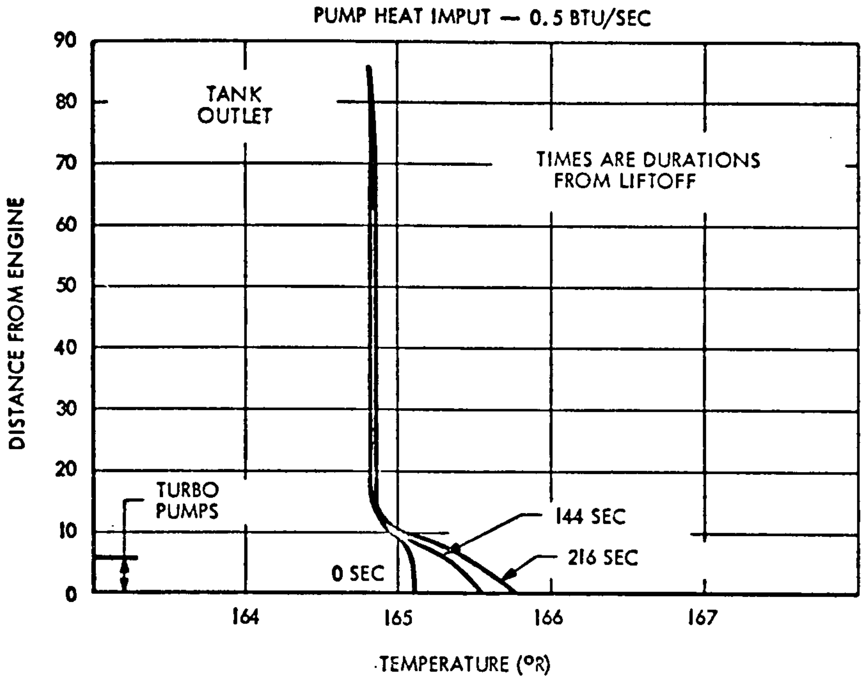

Fig. 9.2-44 Liquid Temperature Profiles, LOX Feedline 0.5-In. NRC-2 Insulation

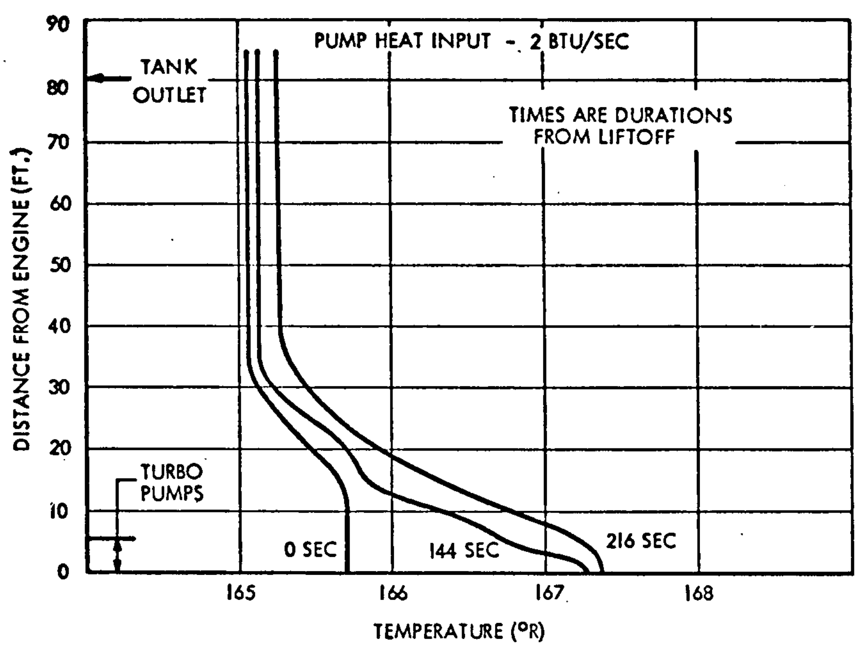

Fig. 9.2-45 Liquid Temperature Profiles, LOX Feedline 1.0-in. Foam Insulation

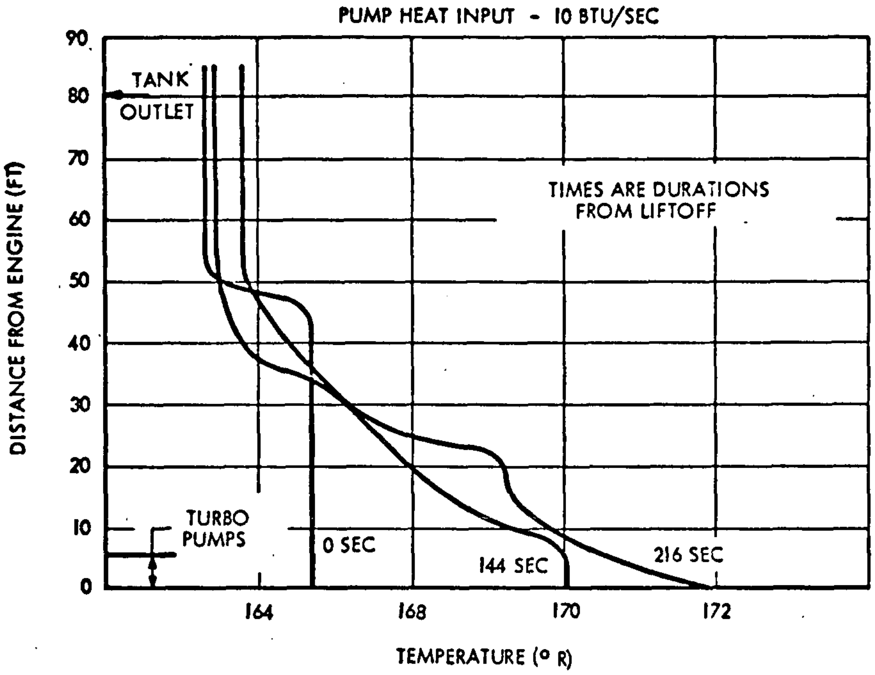

Fig. 9.2-46 Liquid Temperature Profiles, LOX Feedline 0.5-In. Foam Insulation

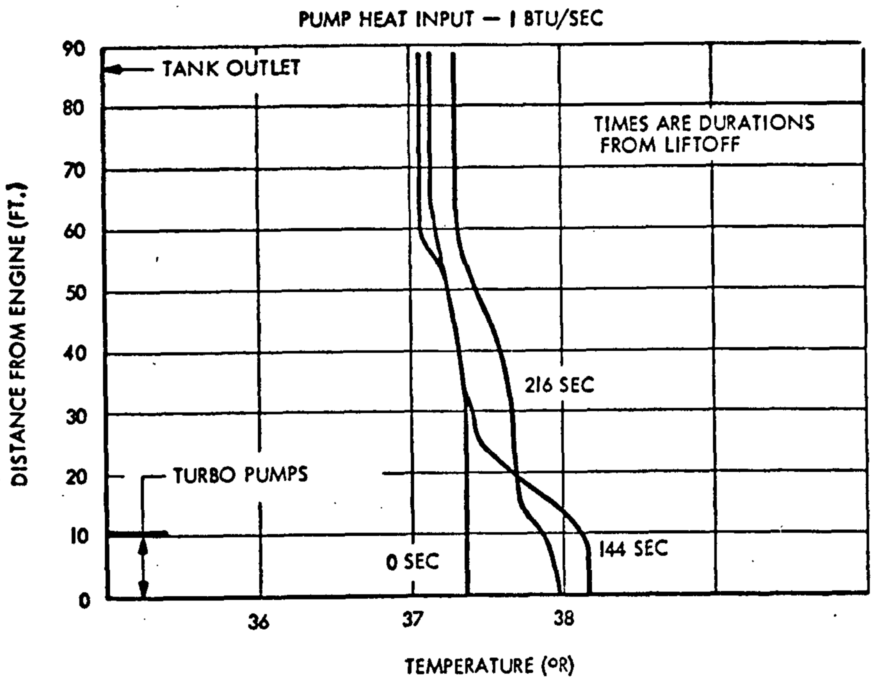

Fig. 9.2-47 Liquid Temperature Profiles, LH_2 Feedline 0.5-In. NRC-2 Insulation

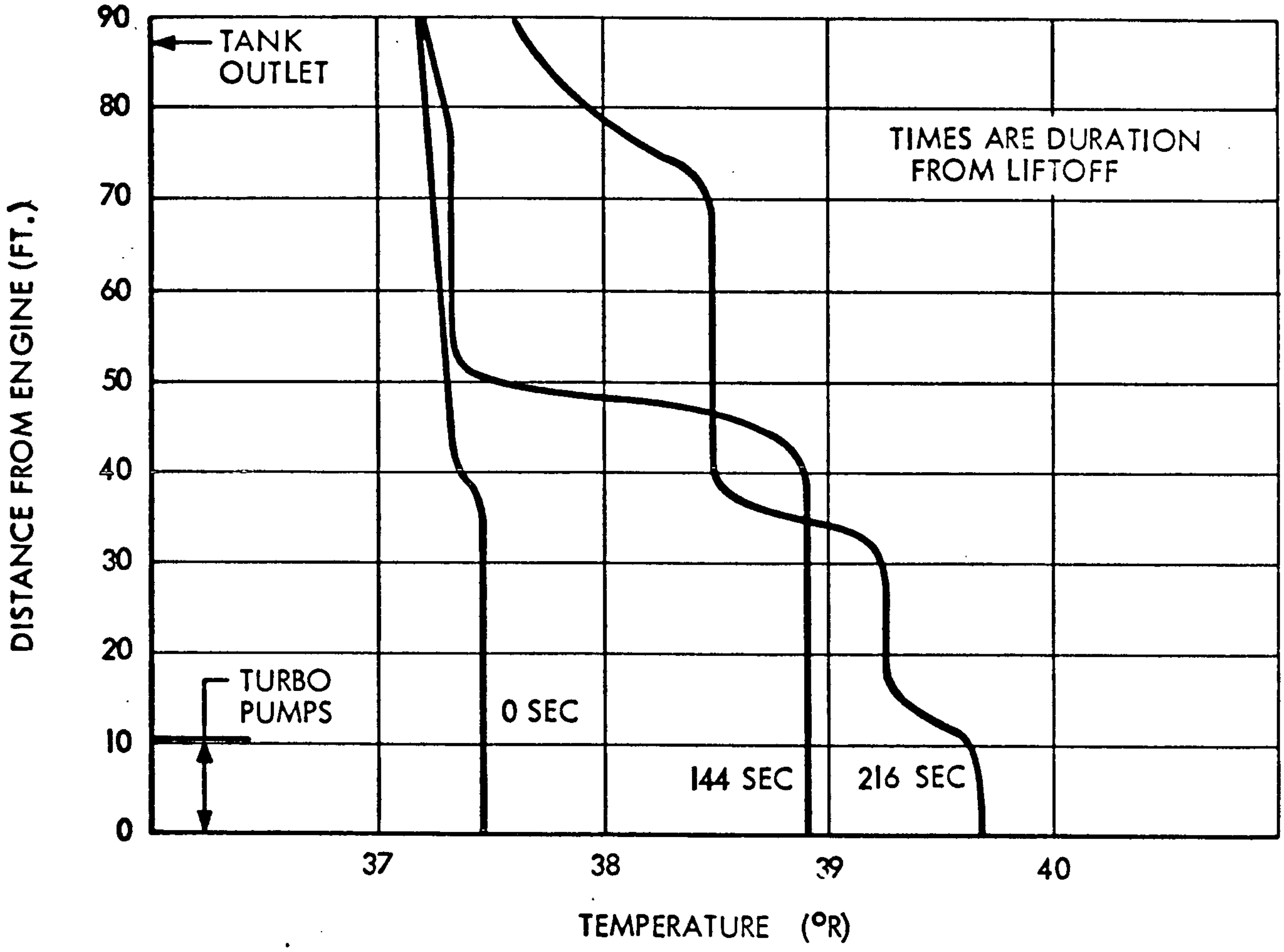

Fig. 9.2-48 Liquid Temperature Profiles, LH_2 Feedline 1.0-In. Foam Insulation

Results of these analyses indicate that with excellent insulation of the pumps and lines, it could be possible to have convective-cooling with temperature rises of less that $1^{o}R$ in the liquid-oxygen and liquid-hydrogen lines. However, for the more practical liquid-oxygen heating rates, the liquid-oxygen temperature rises could be $6^{o}R$. If the pump liquid-hydrogen heating rates are 10 Btu/sec, convection cooling is not possible. For rates that are possibly achievable (with difficulty), convection cooling would produce a $3^{o}R$-to $4^{o}R$ temperature rise.

9.2.2.5. OIPS Feedline Pressure Losses.

9.2.2.5.1 Start-Transient Pressure Losses. The pressure losses during engine start result in design requirements for the feedline sizes. Analyses in this study considered the pressure losses from acceleration but did not consider all propellant feedline dynamics that can result in some increases in the feedline sizes.

Figure 9.2-49 shows the effect of feedline diameter on the minimum OIPS tank pressure requirements for LO_2 and LH_2 tanks, respectively. Pressure requirements are shown for both the MDC and NAR vehicle configurations, using the P&WA engine-start characteristics. These pressure requirements include the line friction ΔP, the component ΔPs (and tolerance), the ΔP required to accelerate the flow, the engine-pump NPSP requirements, and the hydrostatic head effects.

The LO_2 start-transient pressure requirements were set by a flow acceleration of 950 lb/sec^2 which occurs at about 1 sec after the start command. The LH_2 start-transient pressure requirements were set (for the larger line diameter) by a flow acceleration of 15 lb/sec^2, which also occurs at about 1 sec after the start command. However, since the flow acceleration is rather small and very little hydrostatic head is available, the pressure is fairly constant and equal to the NPSP (2 psi) and component ΔP tolerance (3 psi).

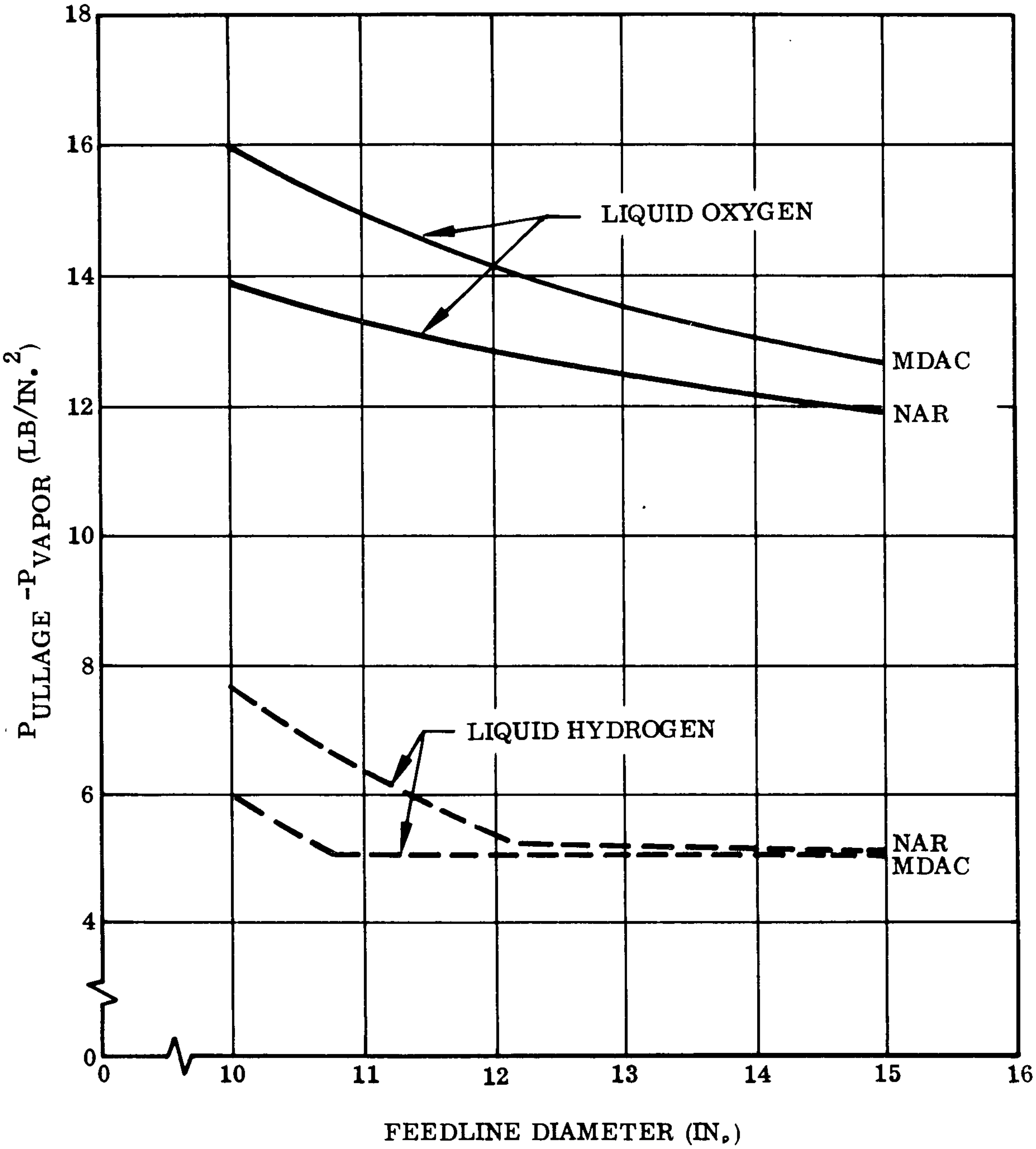

Fig. 9.2-49 OIPS Start Transient Pressure Requirements
(P&WA Engine Start Transient)

For the smaller line size, the pressure requirement is set by a flow acceleration of 157 lb/sec^2, which occurs at about 3.35 sec when the flowrate is large and the associated higher friction ΔP become significant.

Also, evaluations were made to determine the required start ΔP requirements for the maximum conditions listed in the Space Shuttle Engine Interface Control Documents (see Fig. 9.2-50). Note that an engine requiring propellants to be delivered to meet this start transient would result in high-transient pressures.

9.2.2.5.2. Steady-State Feedline Pressure Losses. Data are provided in confirmation of the start transient being the principal pressure drop. In Fig. 9.2-51, steady-state information is provided for liquid hydrogen. For liquid oxygen, the hydrostatic pressure exceeded the NPSP, and friction drop in the line was larger than 10 in. (data not presented).

9.2.2.6. OIPS Shutdown Residuals. An examination was made of the feedline residuals resulting from required residuals to protect the engines during shutdown. The approach used was to locate the terminal shutdown sensors such that at maximum engine-power level the engines would be protected by at least 2-sec of liquid-oxygen flow and at least 4-sec of liquid-hydrogen flow. Locating the sensors at this point, the residuals were assessed for a normal shutdown from 80 percent normal power level.

Data presented in Fig. 9.2-52 are for two feedlines from two tanks feeding the two engines. The weight index consists of the sum of the trapped liquids, the lines, and the components.

As may be seen from these data, the liquid-hydrogen sensors would have to be located in the propellant tanks. For the line sizes under consideration for the orbiter (over 14-in.), the liquid-oxygen sensors would be located in the lines.

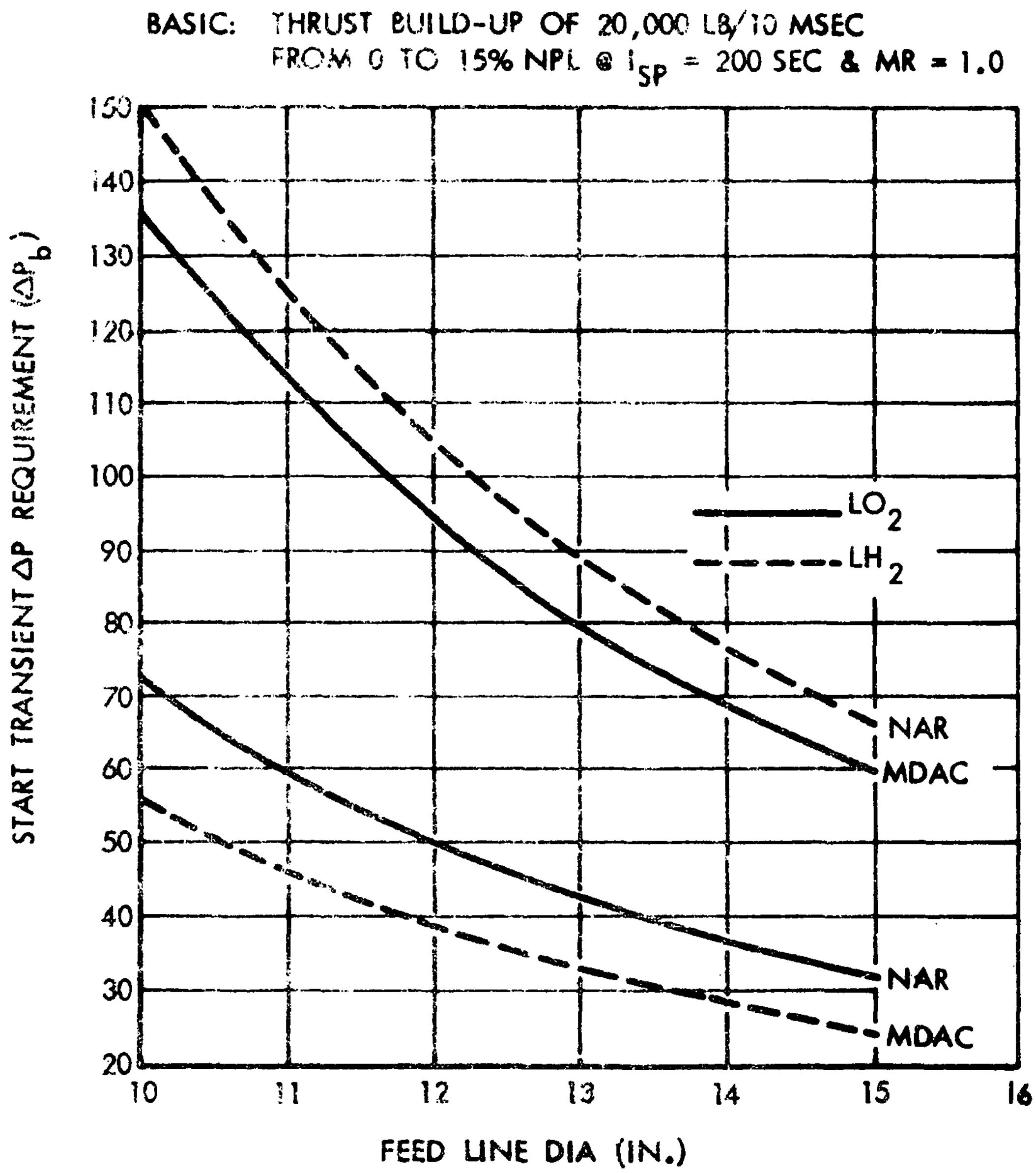

Fig. 9.2-50 OIPS Start ΔP Requirements Based on Maximum ICD Values

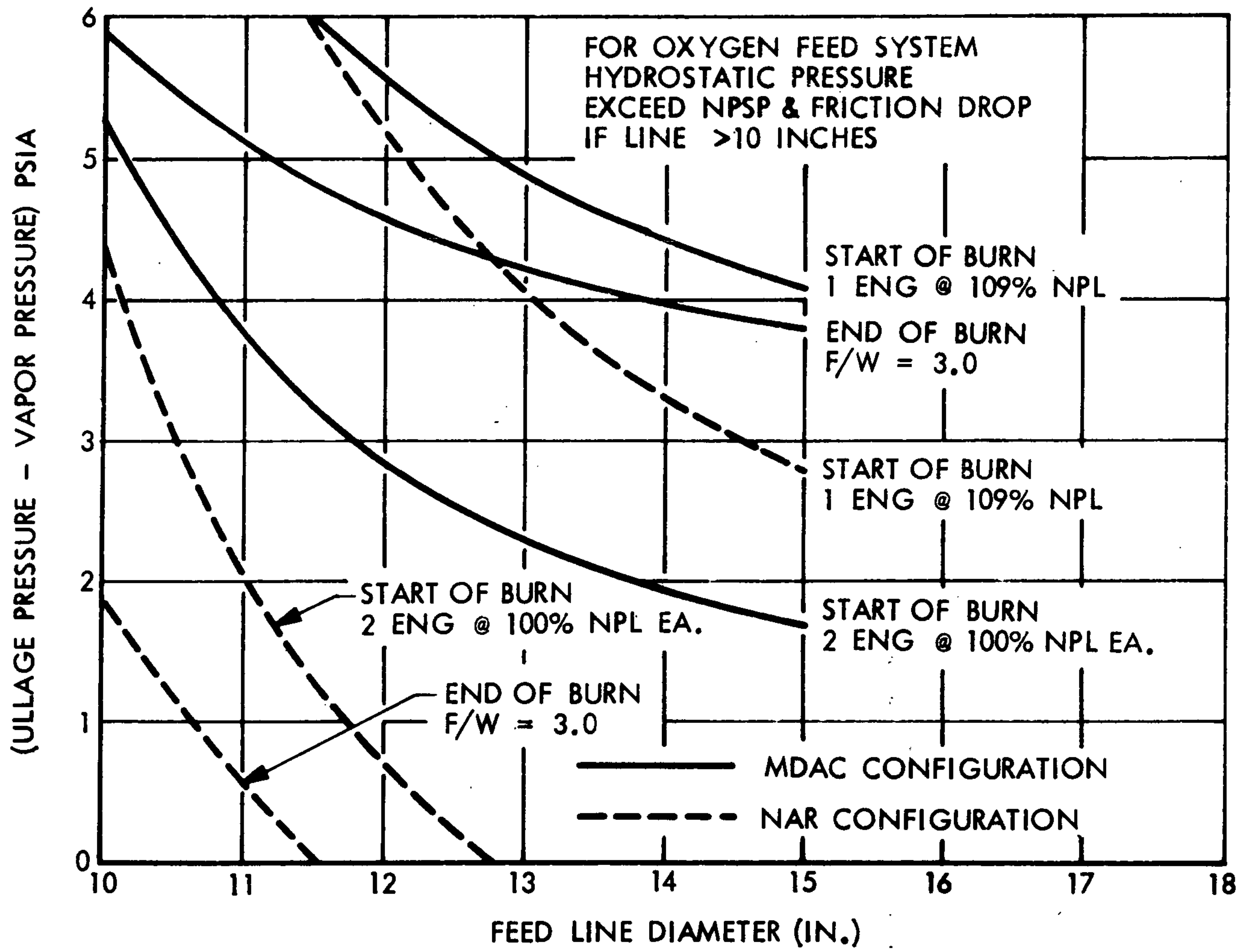

Fig. 9.2-51 Ullage Pressure and Vapor Pressure Difference vs Feedline Diameter at Steady-State LH_2 Feed System

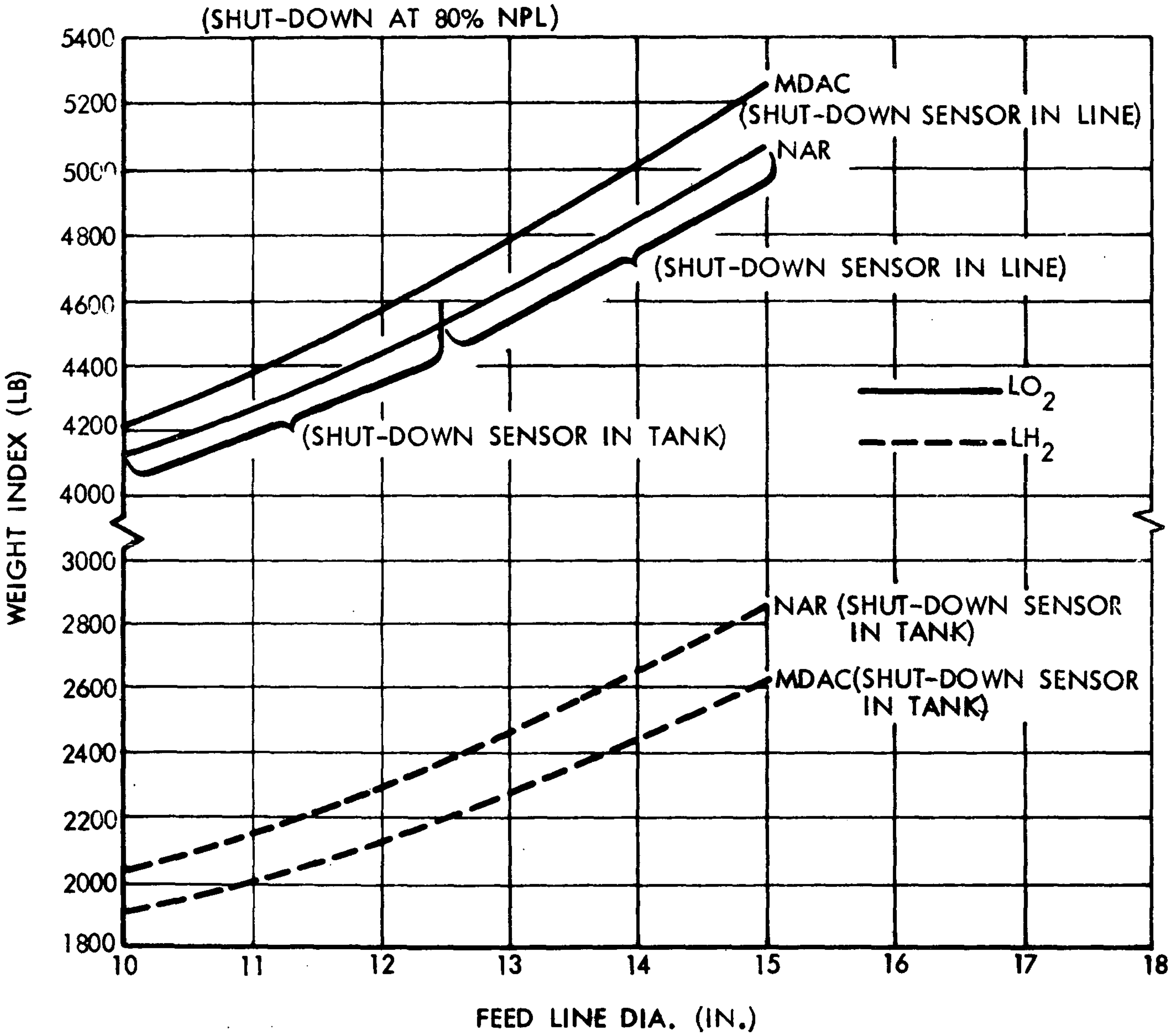

Fig. 9.2-52 Shutdown Weights of Feedlines Components, and Trapped Liquids

B

9.2.2.7 <u>OIPS Tank-Pressure Rise During Reentry</u>. Studies were made of the OIPS tank-pressure histories during reentry. The reentry structural heating profiles and acceleration profiles presented in Figs. 9.2-53 and 9.2-54 were employed. Heat-transfer coefficients in the tanks were varied in accordance with the temperatures and accelerations. Results are presented in Figs. 9.2-55 and 9.2-56.

The shape of the liquid-oxygen curves with no insulation is the result of heat-transfer coefficient variations with acceleration. Liquid-hydrogen tanks with external insulation show a temperature lag with resulting pressure lag.

It appears from these curves that it is desirable to adjust the tank pressures to 18 psia prior to reentry. The resulting rise in tank pressure will not exceed 28 psia.

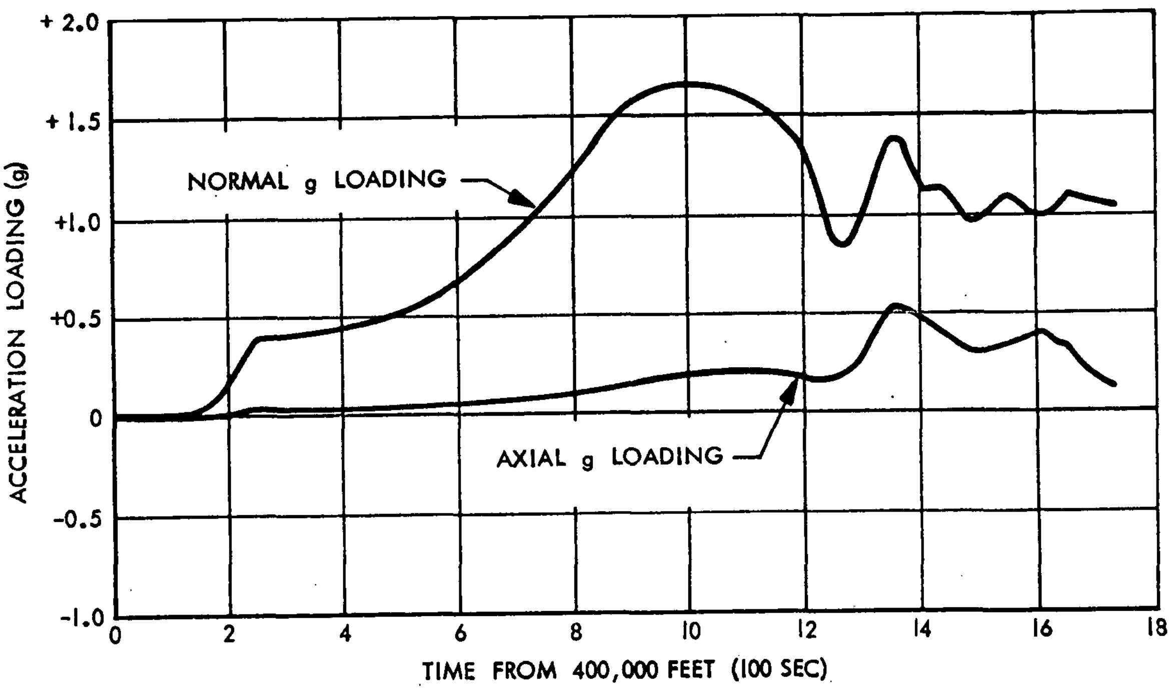

Fig. 9.2-53 Typical Reentry Acceleration (g) (High Crossrange)

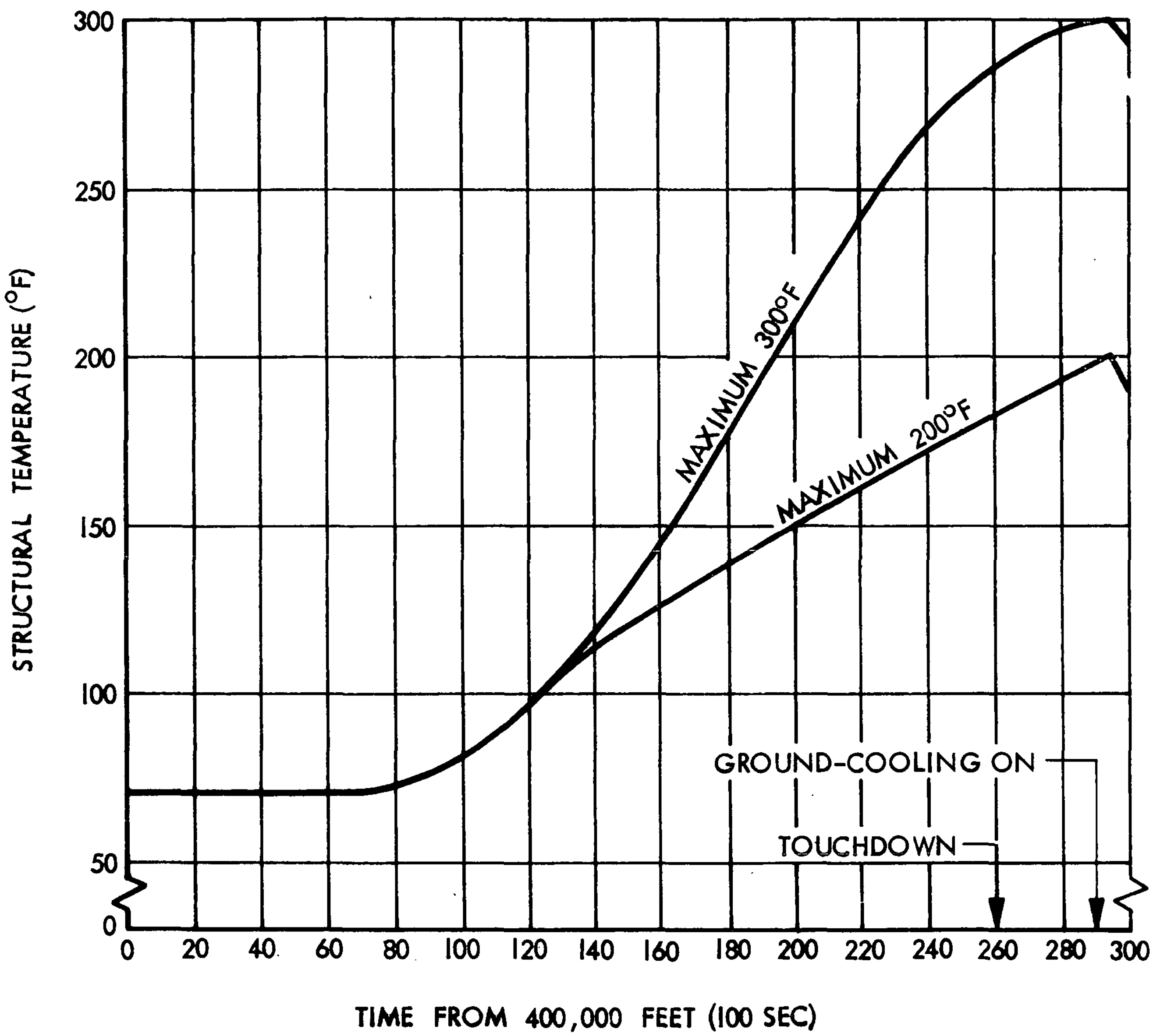

Fig. 9.2-54 Typical Reentry Structural Temperatures (High Crossrange)

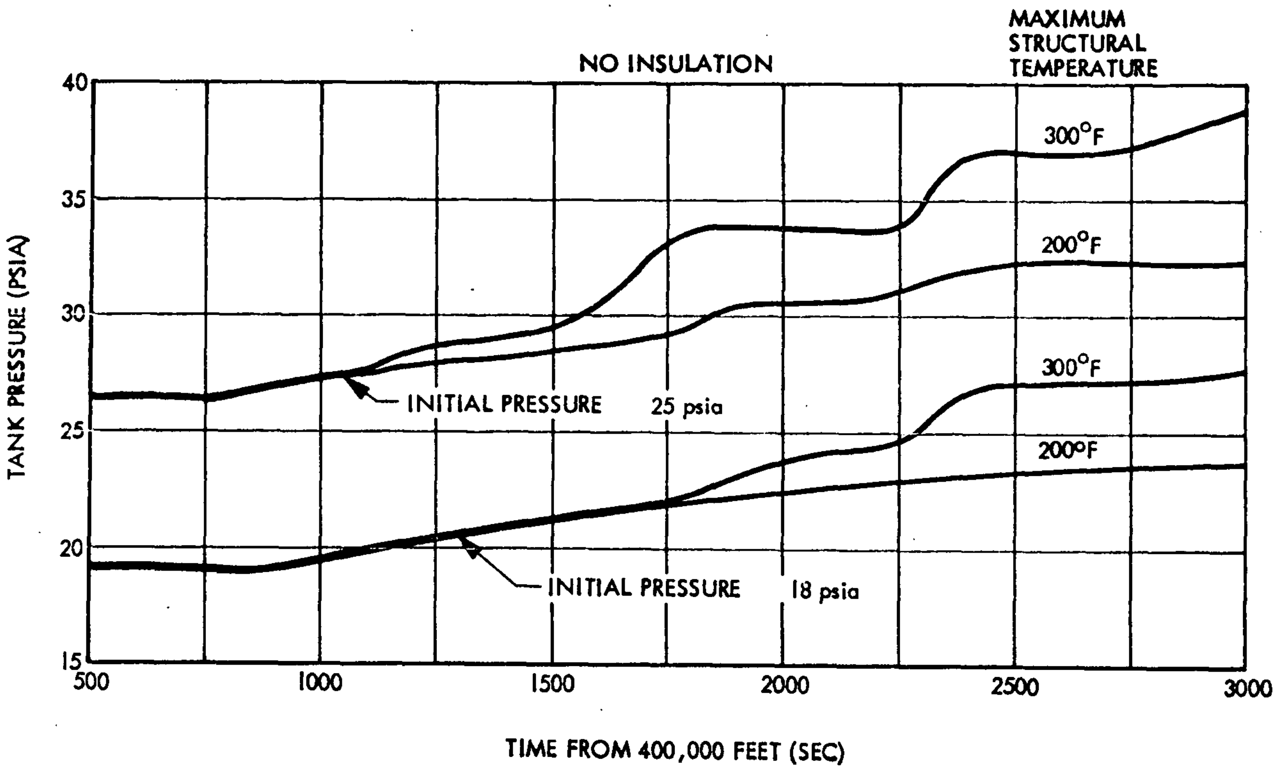

Fig. 9.2-55 Liquid-Oxygen Orbit-Injection Tank-Pressure Rise During Reentry

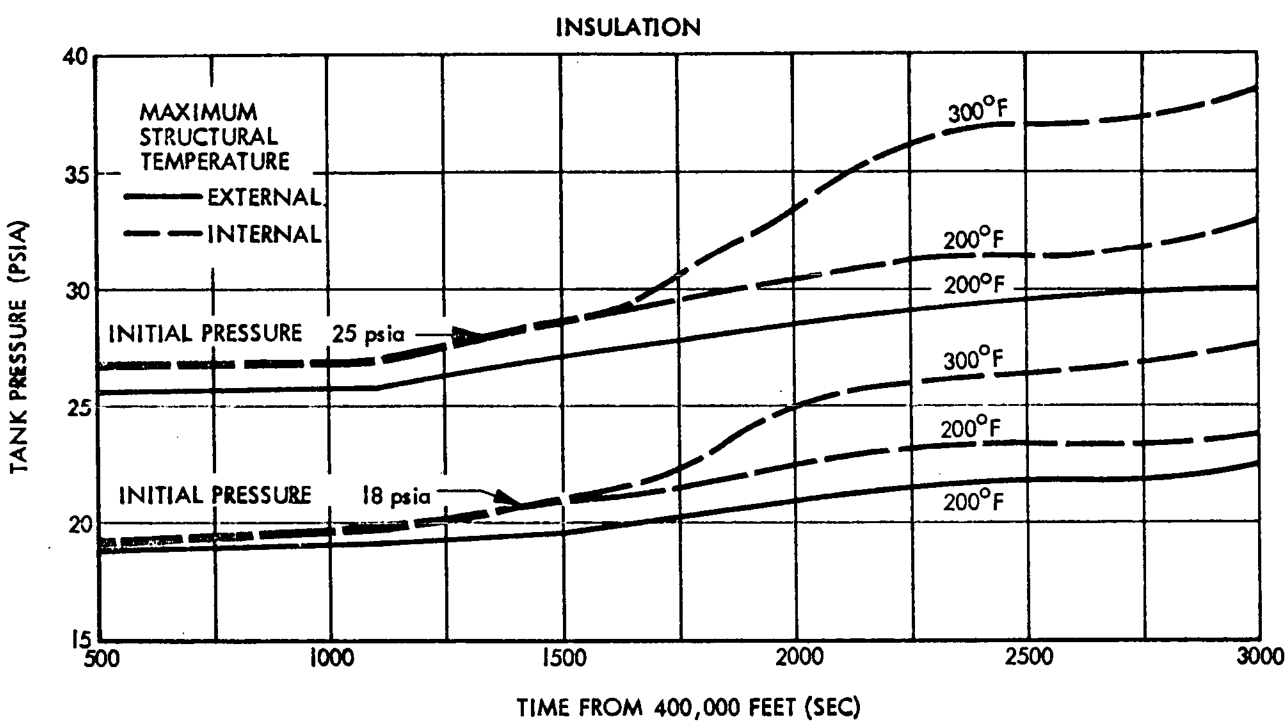

Fig. 9.2-56 Liquid-Hydrogen Orbit-Injection Tank-Pressure Rise During Reentry

9.2.2.8 Propellant Utilization. Detailed propellant utilization analysis for the Orbit Injection Propellant Supply could not be conducted without substantial trajectory and performance data. Variations in the oxidizer/fuel ratio control would have to be examined. The approach to propellant utilization would be to employ a hydrogen fuel bias.

The instrumentation for propellant utilization was defined as optical point sensors, combined as necessary with capacitance probes.

9.2.3 Orbit Injection Propellant Supply Tradeoff Study Results

The Orbit Injection Propellant Supply evaluations resulted in conclusions regarding a number of subsystem issues.

9.2.3.1 Pressurization Results. The pressurization analysis results answered several questions of interest to NASA.

9.2.3.1.1 Comparison of Modulated and Constant Bleed Modes of Pressurization. In the pressurization analyses, the important factors related to potential performance loss were:

- Residuals gases left in the tanks
- Propellants lost by venting (constant bleed case only)

The pressurization analyses indicated that there existed insignificant differences between the modulated (on-off) and the constant bleed pressurization modes with regard to these important performance factors.

9.2.3.1.2 Self-Pressurization of Liquid Oxygen Tanks. The liquid-oxygen tanks offer a potential for self-pressurization because of the available hydrostatic head. The analyses indicated that this was feasible for noninsulated tanks, provided the heating rates are high enough. It appears to be a marginal approach and is not recommended.

9.2.3.1.3 Employment of Common Venting and Pressurization Lines. It was determined that the required vent line size to provide for the flowrate during fill operations is approximately 6 in. This line size is also compatible with the pressurization line size. A common vent and pressurization line is considered to be a satisfactory approach.

9.2.3.2 Prepressurization Results. Prepressurization is considered to be separate from the pressurization, both in analysis and subsystems. In a system pressurized by engine bleed, prepressurization is a separate subsystem function. Several prepressurization possibilities exist:

- Prepressurize on the ground with helium prior to launch
- Prepressurization from an onboard system prior to engine start by:
    a. Helium
    b. Stored propellant gases

The analyses indicated that the onboard prepressurization subsystem was not a large weight penalty. Also, it provided flexibility in operation.

9.2.3.3 Effects of Insulation on the OIPS. A minimum insulation thickness is required on the hydrogen propellant tanks in order to prevent air liquification and excessive icing. The effects of any additional insulation was examined for factors that would influence system performance such as:

- Residual gases
- Vented propellant
- Pressurant mass flowrates.

The results indicated that the insulation thickness or the thermal conductivity had little effect on these factors.

9.2.3.4 Feedline Temperature Control. The feedline temperature control was examined for:

- Forced circulation mode
- Natural convection mode

The effects of insulation thickness and effectiveness were examined for each of these modes.

9.2.3.4.1 Forced Circulation in Feedlines. The studies indicated that there was not a large sensitivity of temperature rise to feedline size as a function of flowrate over the range of line sizes from 12 to 18 in. Also, there was only a small sensitivity to the insulation thickness or effectiveness, including vacuum jacketing. Circulation was identified as the most effective parameter in feedline temperature control. The flowrates were sufficiently high to require pumping.

9.2.3.4.2 Natural Convection. Natural convection in the shuttle feedlines was examined, considering that for some of the designs, the lines are relatively vertical. Different insulation thicknesses were examined. The heat input at the pump was varied.

Results of these analyses indicate that with excellent insulation of the pumps and lines, it could be possible to have convective-cooling with temperature rises of less than $1^{\circ}R$ in the liquid-oxygen and liquid-hydrogen lines. However, for the more practical liquid-oxygen heating rates, the liquid-oxygen temperature rises could be $6^{\circ}R$. If the pump liquid-hydrogen heating rates are 10 Btu/sec, convection cooling is not possible. For rates that are possibly achievable (with difficulty), convection cooling would produce a $3^{\circ}R$ to $4^{\circ}R$ temperature rise.

9.3 ATTITUDE CONTROL PROPELLANT SUPPLY (ACPS)

The Attitude Control Propellant Supply subsystem analyses, sensitivity studies, and tradeoff studies were very dependent upon the technology studies:

- "Space Shuttle High Pressure Auxiliary Propulsion Subsystem Definition", NAS 9-11013, performed by TRW Systems.
- "Space Shuttle High Pressure Auxiliary Propulsion Subsystem Definition Study", NAS 8-26248, performed by McDonnell Douglas Astronautics.

By direction, the low-pressure ACPS studies were not considered other than in the initial planning phases of the contract.

A major portion of the Attitude Control Propellant Supply effort was expended in the examination of the liquid/liquid ACPS. This concept, originated by NASA/MSC during the course of the study, was found to be an approach that is comparable with the current gas/gas systems.

The overall approach employed in the ACPS sensitivity and tradeoff studies is presented in Fig. 9.3-1.

9.3.1 Selection of Candidate Subsystems

The spacecraft layouts are presented in Section 4.

Early in the study, the overall approach taken by LMSC, with NASA/MSC approval, was to limit the functions of ACPS so that the large ΔV requirements of the OMPS mission were not included. System candidates were selected so as to minimize the associated technology problems.

Having established that the thruster would be operated under high-pressure, the principal alternatives then become:

- Subcritical storage - pump pressurized
- Supercritical storage - pressure fed

Various possible alternatives within the subsystems are presented in Fig. 9.3-2 for the subcritical approach and in Fig. 9.3-3 for the supercritical approach.

9.3.1.1 Schematics for Components Evaluation at AiResearch. Schematics for the ACPS systems were prepared and submitted to AiResearch for the selection of components. These schematics, presented in Appendix E, were formulated to represent the possible ACPS component arrangements presented in Figs. 9.3-2 and 9.3-3. Also, these schematics were used to perform the initial redundancy analyses using the SETA II computer program. The identified redundancies (presented in Appendix E) established the least-reliable components in the subsystems.

9.3.1.2 Schematics for Sensitivity and Tradeoff Studies. Detailed schematics were prepared for the ACPS concepts tradeoff and evaluation studies. The schematics were put through several iterations, which were principally the result of examinations regarding compliance with safety criteria and instrumentation and control.

9.3.1.2.1 Subcritical Storage (Turbopump Pressurized). The schematic employed in the sensitivity and tradeoff studies is presented in Fig. 9.3-4. As a result of technology recommendations from the AiResearch Company, the hotside of the heat exchanger was limited to 2200 ^{o}R, and both the heat exchanger outlet and the turbine outlet gases were dumped overboard. Evaluations early in the study indicated that the multi-axis propellant orientation required for the ACPS system eliminated the need of propellant gas pressurization, since the entering gas cools or condenses if bubbled

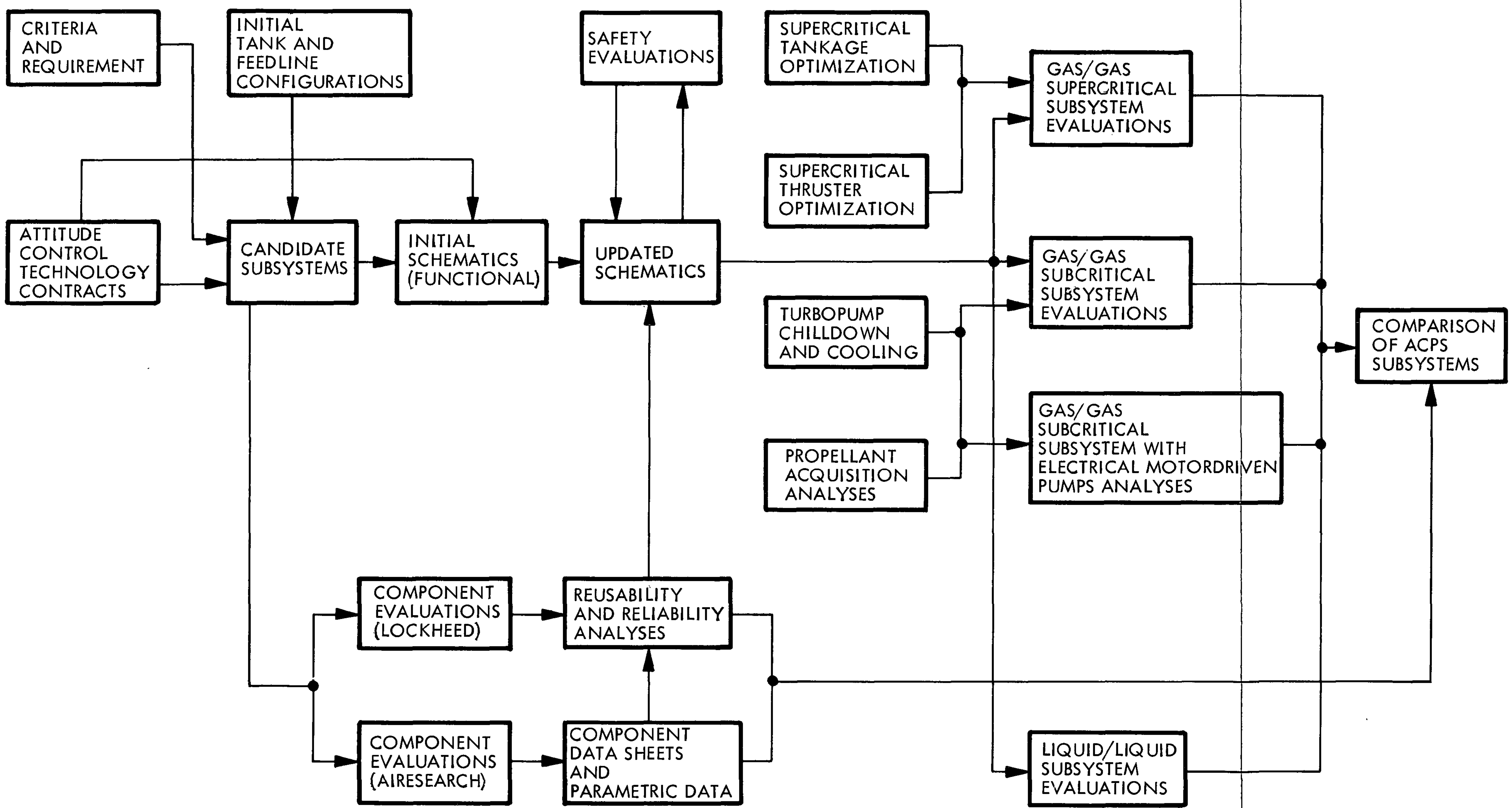

Fig. 9.3-1 Approach to Attitude Control Propellant Supply Evaluations

FOLDOUT FRAME 1

FOLDOUT FRAME 2

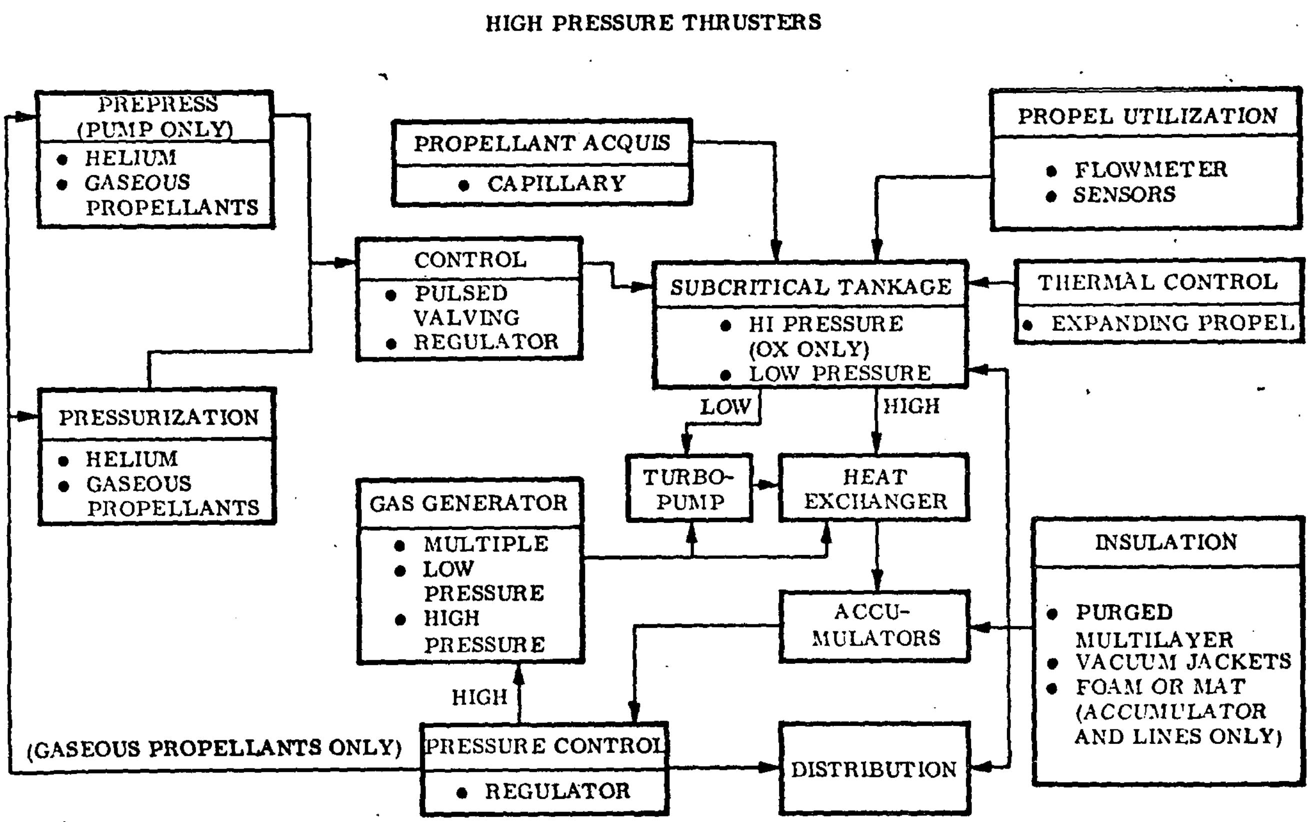

Fig. 9.3-2 Attitude Control Propellant System

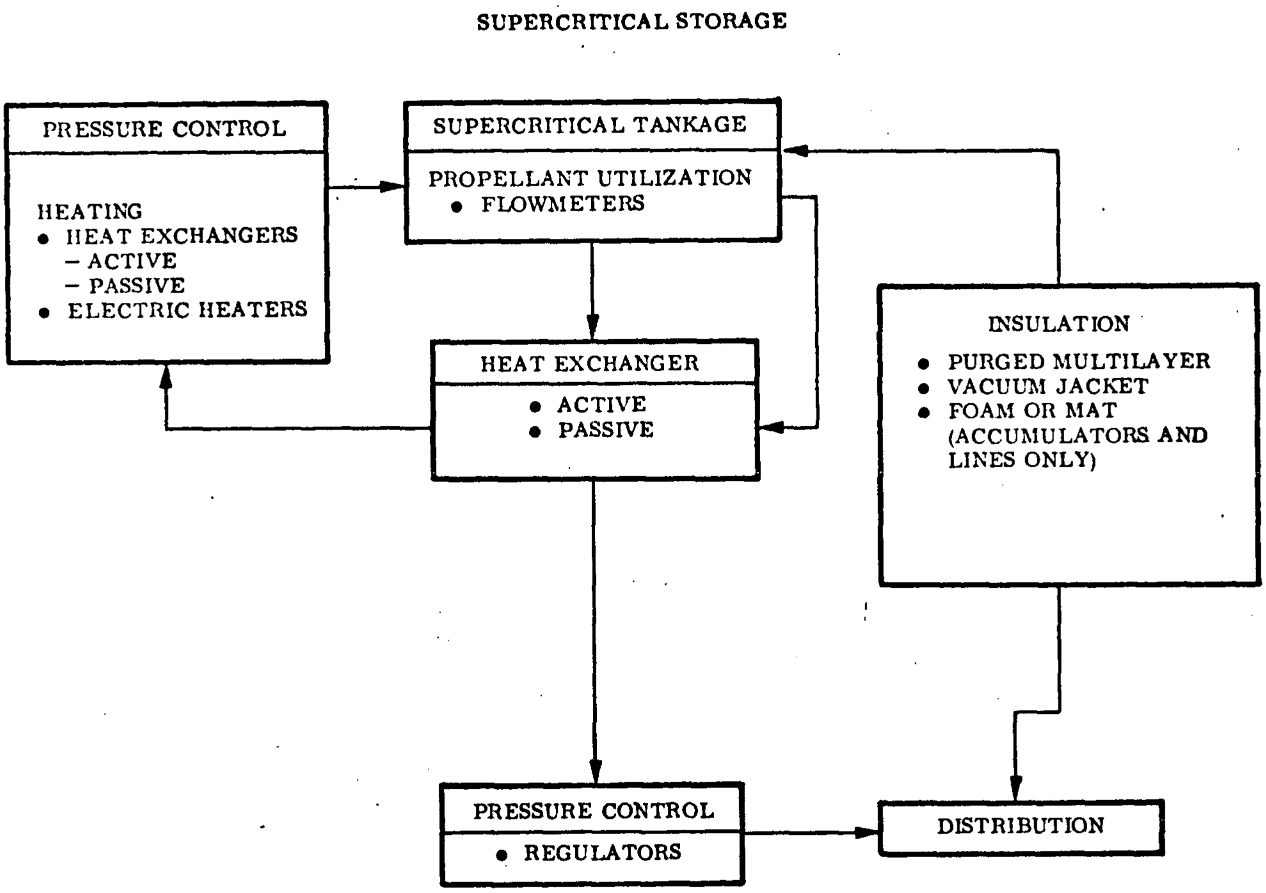

Fig. 9.3-3 Attitude Control Propellant System

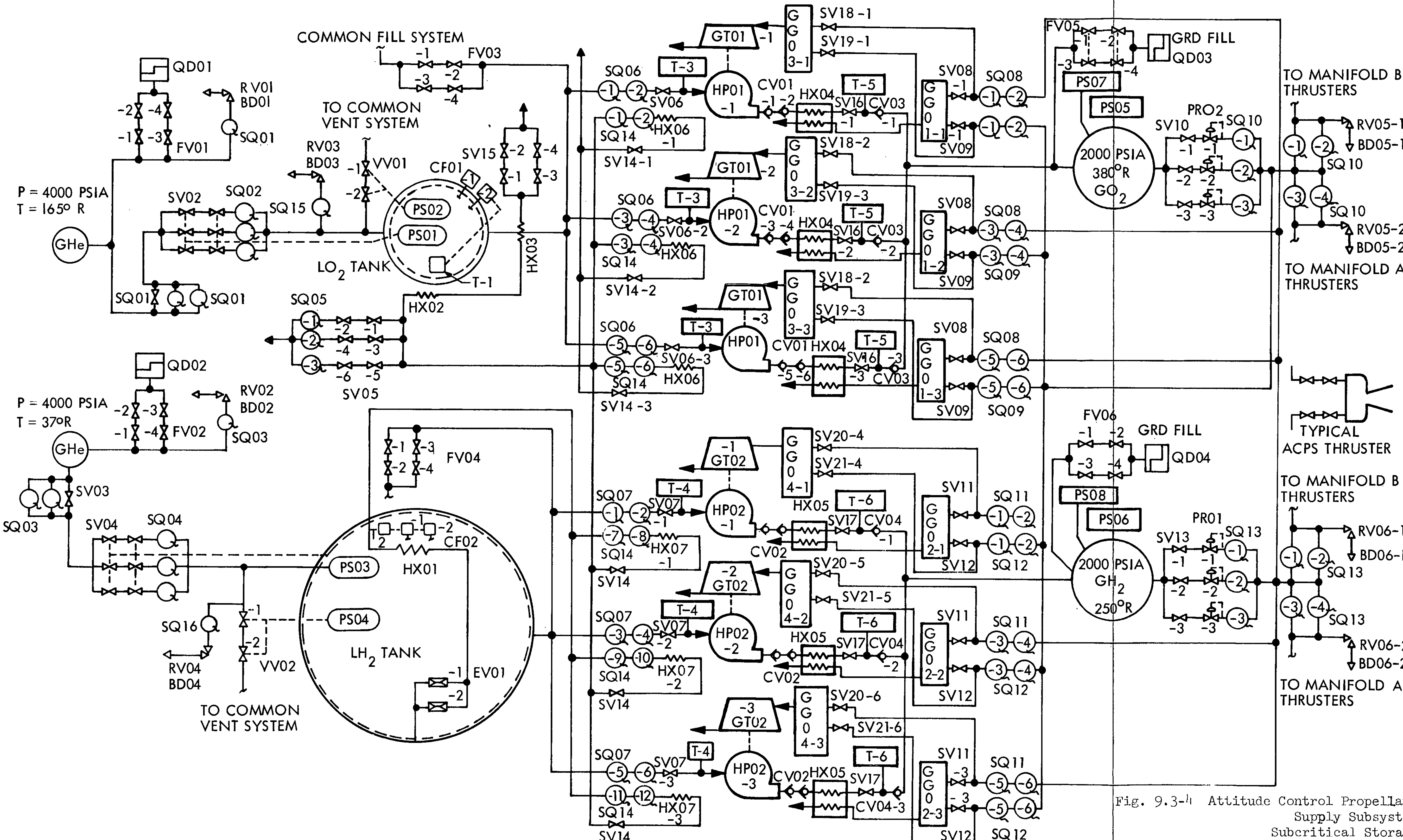

Fig. 9.3-4 Attitude Control Propellant Supply Subsystem Subcritical Storage

through the liquid propellants, resulting in unreliable tank pressures. Helium is used for pressurization where continuous restart capability in all axes is required.

9.3.1.2.2 Subcritical Storage (Electric-Motor-Driven Pump). A variation of the subcritical storage is to use an electric-motor-driven pump rather than a turbopump.

9.3.1.2.3 Supercritical Storage. The schematic employed in the sensitivity and tradeoff studies is presented in Fig. 9.3-5. This schematic represents a relatively conventional approach to the supercritical storage.

9.3.2 Detailed Subsystem Analyses and Sensitivity Studies

As previously mentioned, where possible, the Attitude Control Propellant Supply analyses relied heavily upon the results of the technology contracts in progress. It was necessary to perform the major portion of the analyses on the supercritical and the liquid/liquid systems.

9.3.2.1 Liquid/Liquid Attitude Control Propellant Supply.

9.3.2.1.1 Turbopump System. The possible advantages of a liquid/liquid ACPS system was recognized by NASA/MSC during the contract performance. LMSC was asked to examine this system, in which the propellants are supplied to the ACPS engine as liquid rather than as gas. A typical thermodynamic cycle is shown in Fig. 9.3-6. Saturated liquid is pumped from the storage tank (state point 1) to the engines and accumulator (at state point 2) at a pressure P_2. When flow to the engines is no longer demanded, the distribution system is at pressure P_2 and the pumps are stopped. Circulation fans, located at each engine cluster and accumulator, are used to continuously circulate the fluid so that it is always homogeneous throughout the entire distribution system. As heat enters the system, the pressure rises to a maximum of 500 psia and reaches state point 3.

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Additional heat that enters the system is withdrawn by venting the fluid in the lines and accumulator back into the storage tank, where it is then removed by means of a tank thermal control refrigeration loop. If state 4 (determined by the maximum allowed temperature) is reached prior to engine flow demands, the pumps are started, delivering a low flowrate at 500 psia and, thus, replenishing the warm fluid with cold fluid. If the engines require flow prior to or upon reaching state 4, the helium in the accumulators will provide the pressure to supply the required flow until the pressure decays to P_5, at which time the pumps are started to supply the engines and refill the accumulators with liquid to be ready to repeat the cycle. A simplified schematic that follows this cycle, shown in Fig. 9.3-7, depicts the pumps, accumulator, accumulator, and the relief valve, which serves to vent propellants back into the storage tank after the fluid reaches state 3.

Table 9.3-1 shows the primary study considerations used in this analysis.

The accumulator size is determined by the desired amount of propellant to be used between pump cycles (an increase in this parameter reduces the number of pump cycles), the pump start time (t_s), and the maximum allowed temperature (T_4). Figures 9.3-8 and 9.3-9 show the effect of these parameters on the required accumulator volume.

These accumulators act like a pneumatic spring, using helium as the gas. Also, the mass of helium required is a function of the same parameters as the accumulator size. The effect of these parameters on required helium mass is shown in Figs. 9.3-10 and 9.3-11.

The pressure setting at which the pumps must be started during engine flow demand is determined so that sufficient propellant is in the accumulator to sustain full engine flow for the time required for the pumps to come up to speed (t_s). Figures 9.3-12 and 9.3-13 show the minimum pressure at which the pumps must be started to assure that the engines have a continuous propellant supply.

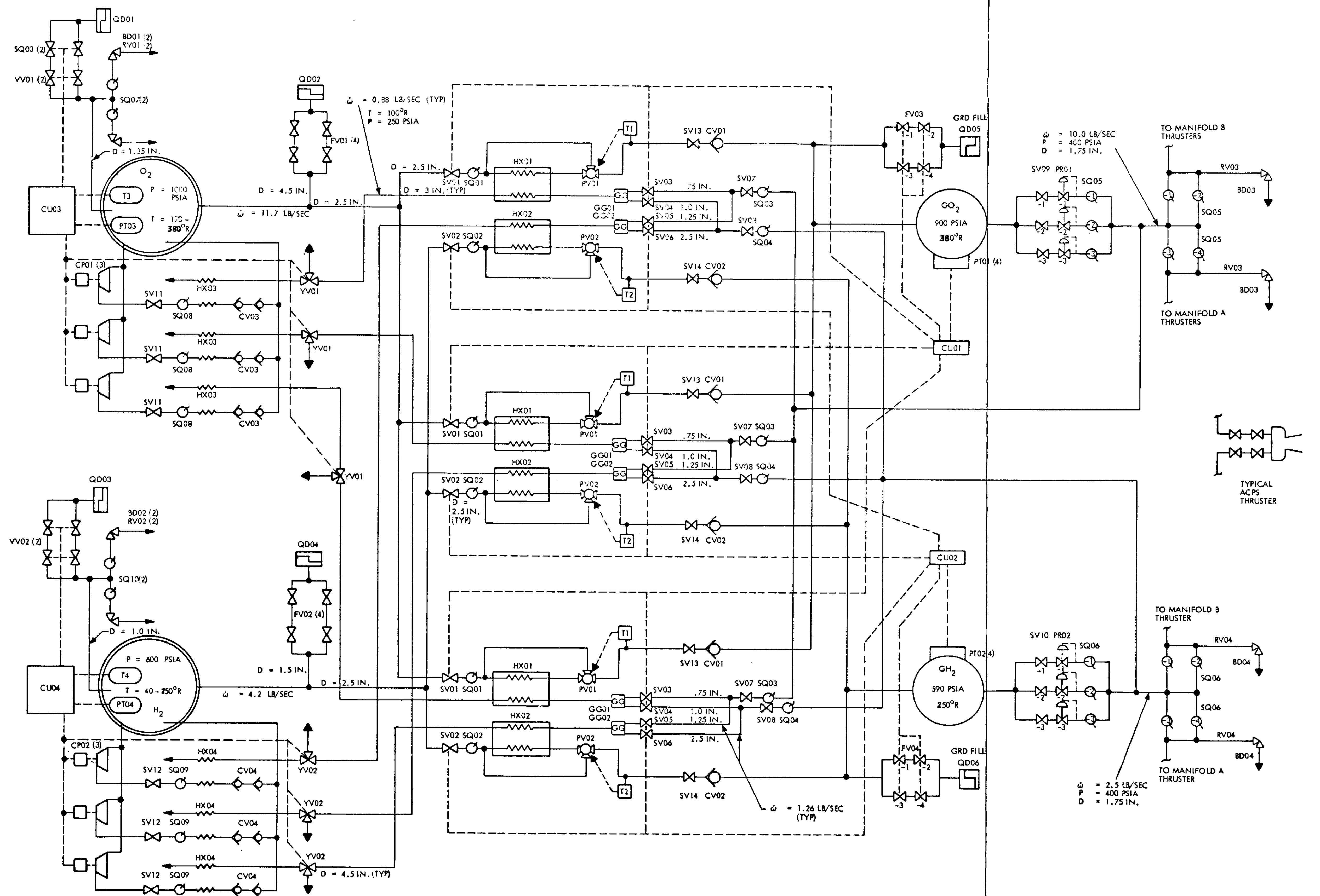


Fig. 9.3-5 Attitude Control Propellant Supply System Supercritical Storage

FOLDOUT FRAME 1

FOLDOUT FRAME 2

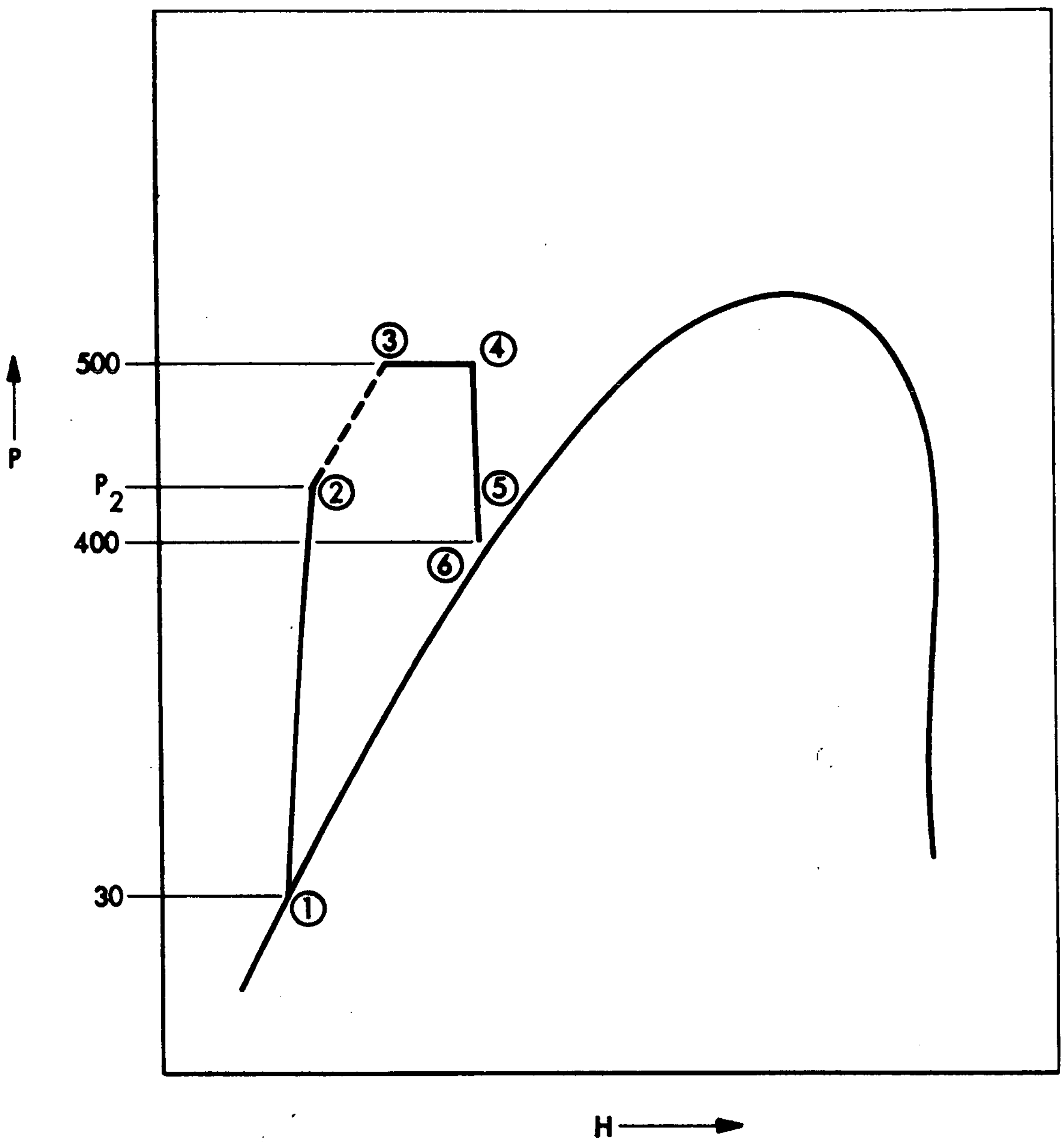


Fig. 9.3-6 Liquid/Liquid ACPS Thermodynamic Cycle

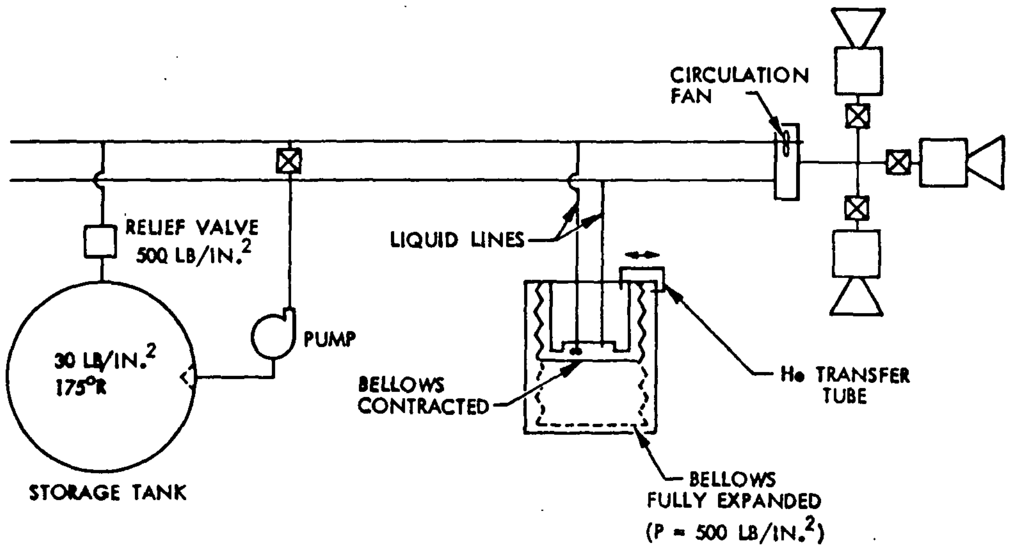


Fig. 9.3-7 Liquid Feed ACPS Schematic

Table 9.3-1

LIQUID ACPS STUDY CONSIDERATIONS

THERMODYNAMIC CYCLE:	OPERATING PRESSURES (400 – 500 PSIA) OPERATING TEMPERATURES (O_2: 175 – 248°R H_2: 37 – 72°R)
ACCUMULATOR/BELLOWS PARAMETRIC STUDY:	VOLUME REQUIREMENTS He REQUIREMENTS ENERGY STORAGE CAPABILITY PUMP REQUIREMENTS
LINE STUDY:	DIAMETER (1 IN.) HEAT LEAK (INSULATION AND VACUUM JACKETING) ENERGY STORAGE CAPABILITY
SYSTEM PERFORMANCE:	ENGINE I_{SP} (423 SEC) SYSTEM I_{SP} (420 SEC) HEAT BALANCE (H_2 COOLANT REQUIREMENTS)
SYSTEM WEIGHT:	DRY WEIGHT RESIDUALS EXPENDABLES

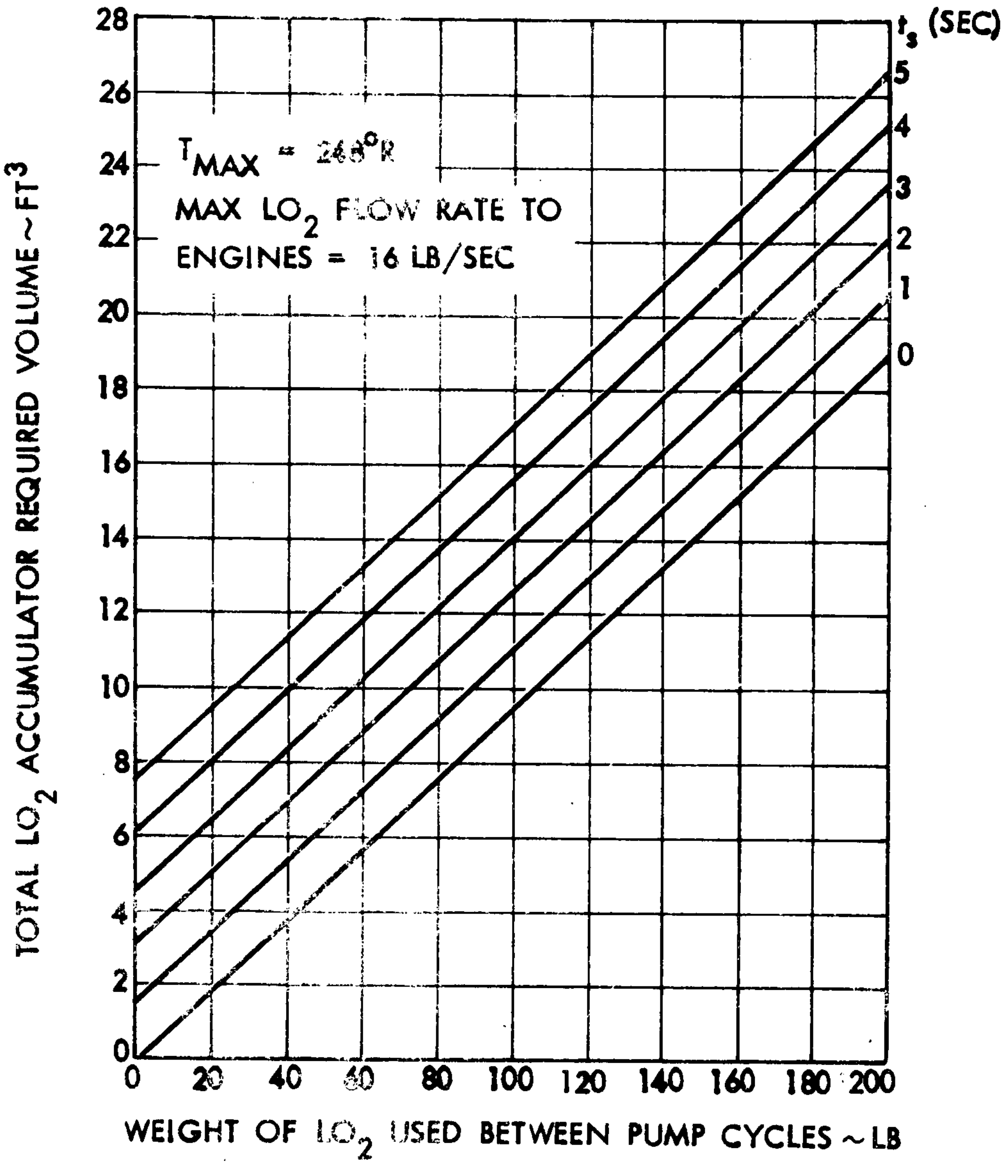


Fig. 9.3-8 LO_2 Accumulator(s) Volume Requirements

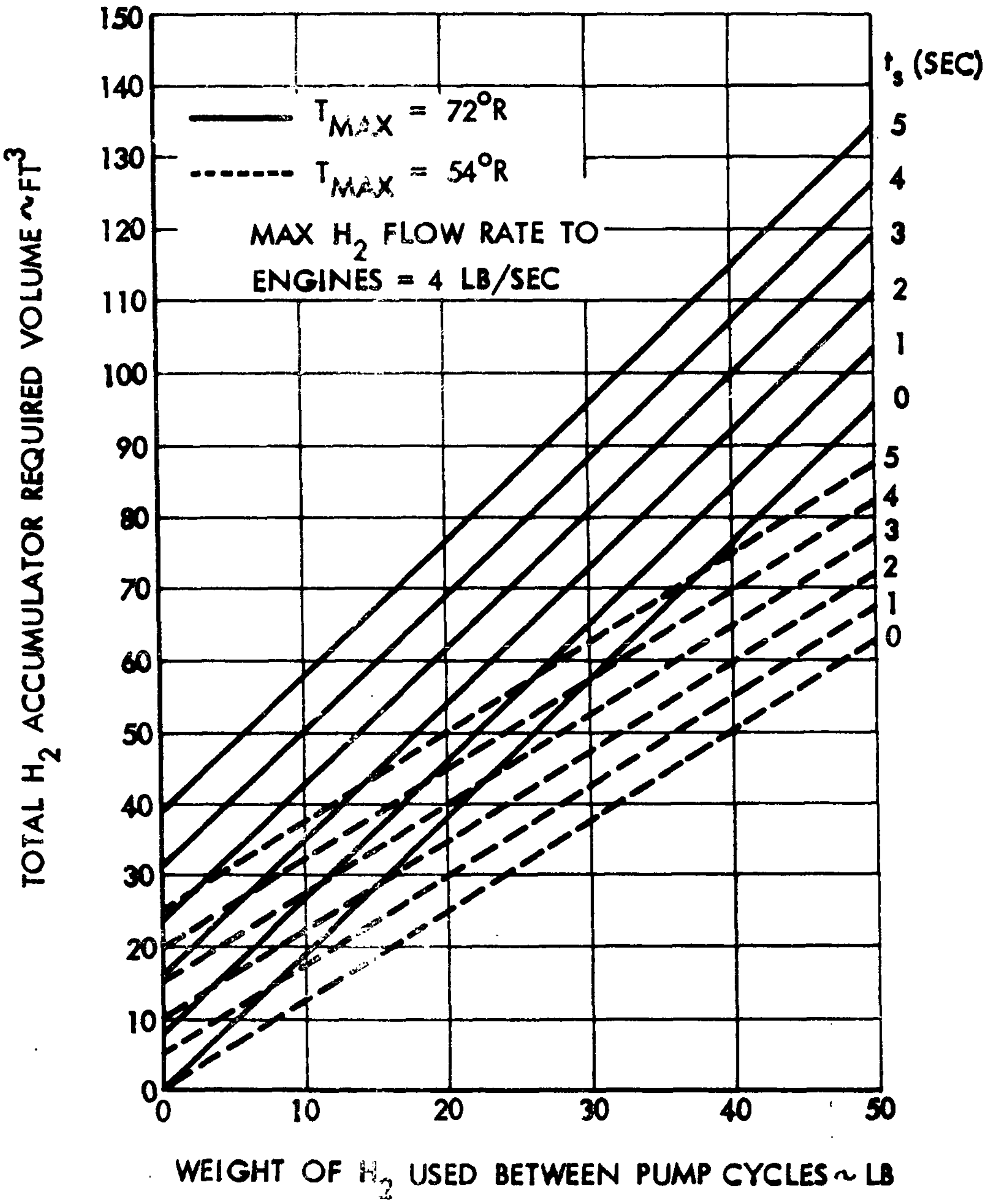


Fig. 9.3-9 H_2 Accumulator(s) Volume Requirements

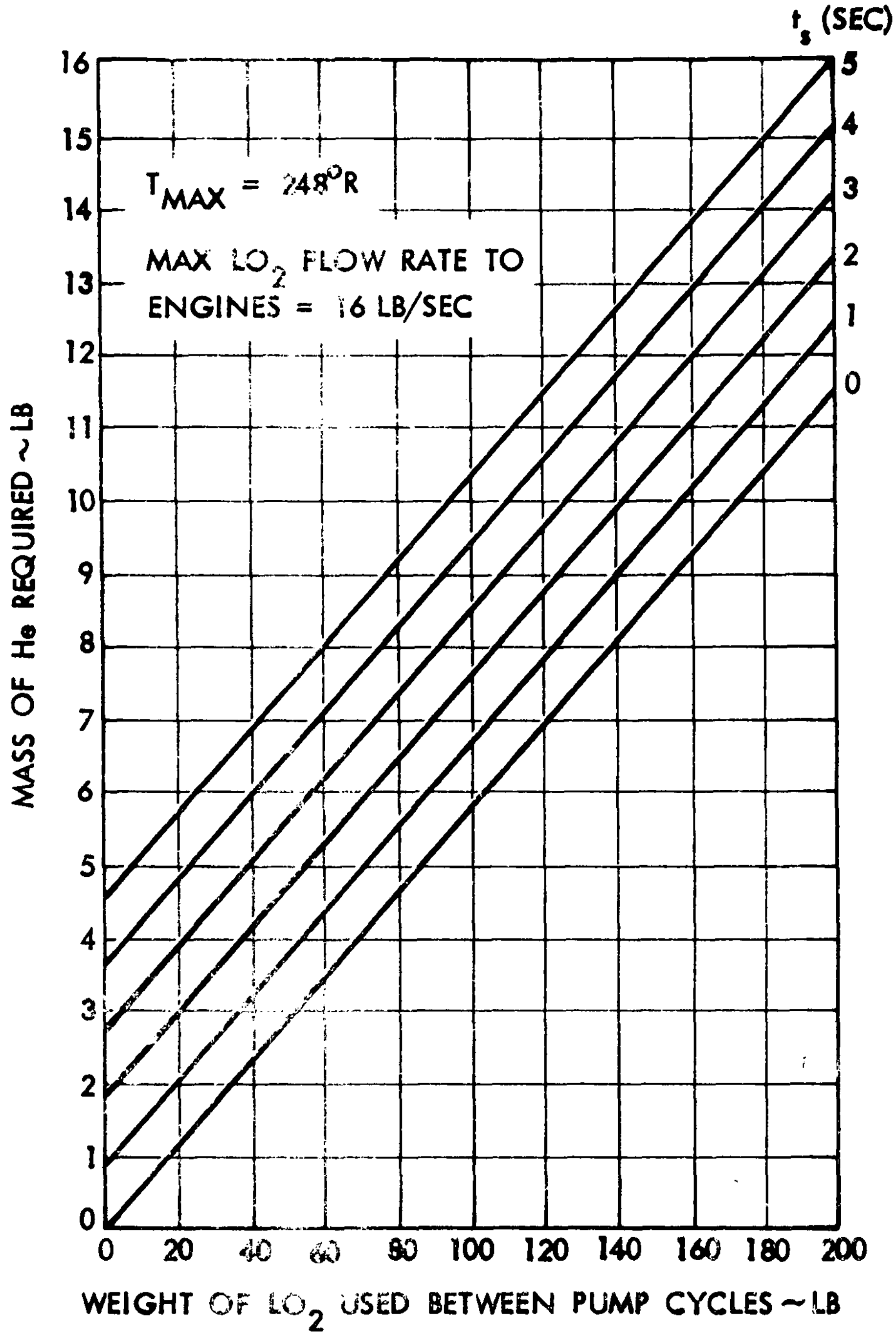


Fig. 9.3-10 He Requirements for LO_2 System

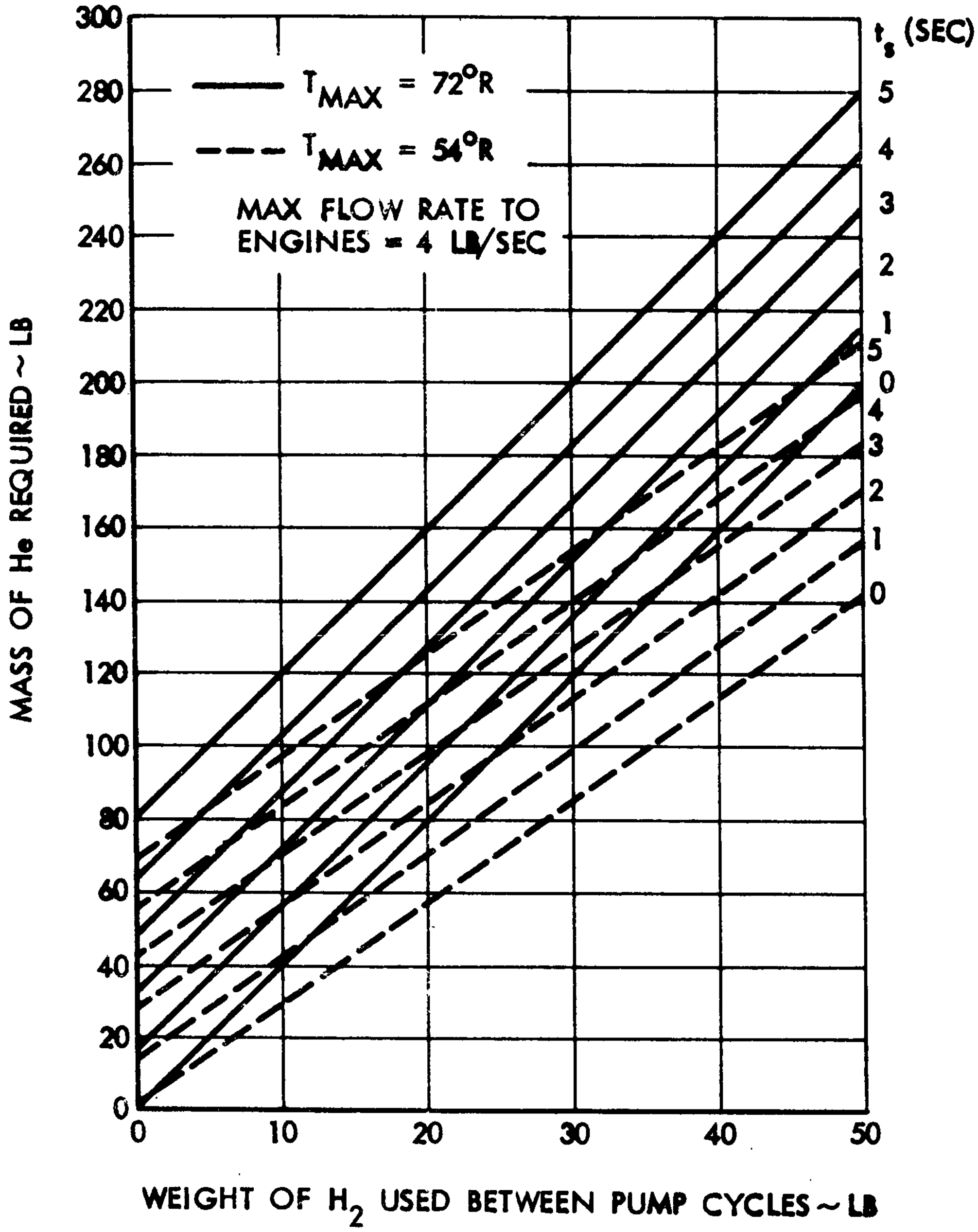


Fig. 9.3-11 He Requirements for H_2 System

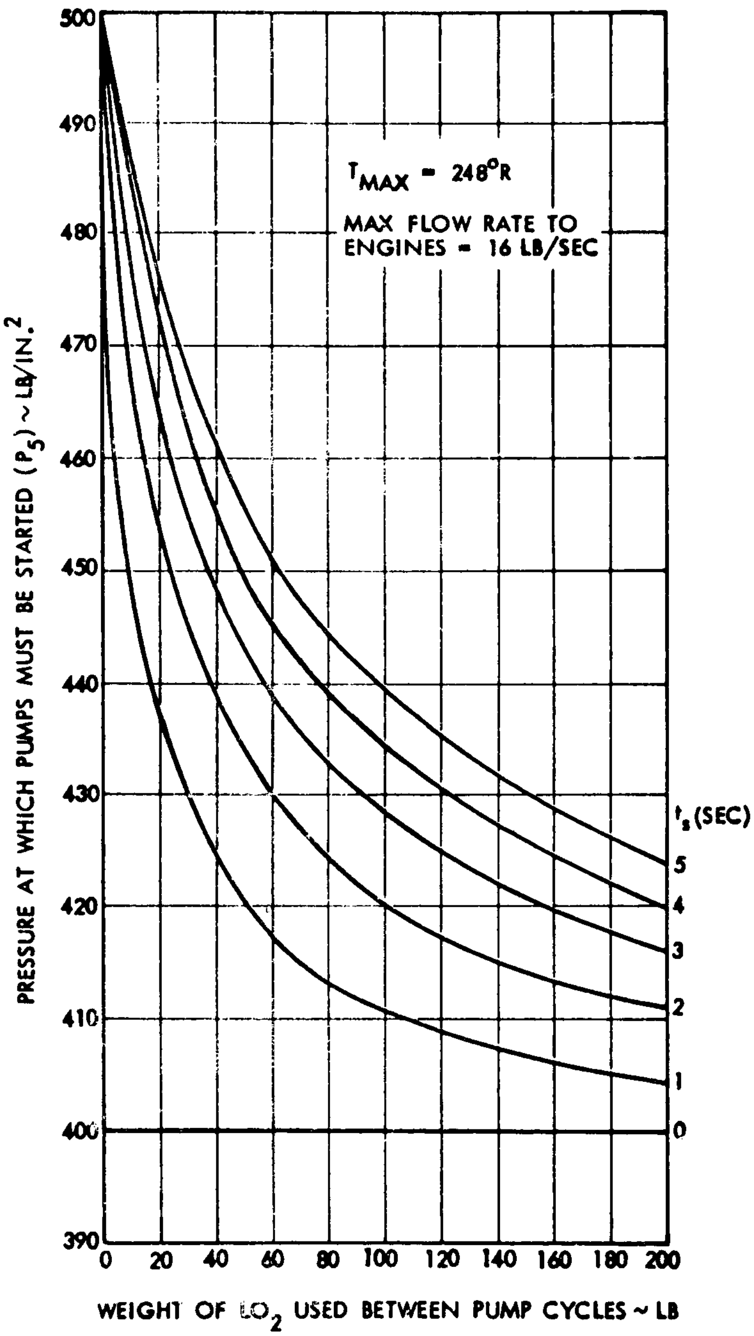


Fig. 9.3-12 LO_2 Accumulator Minimum Pressure Prior to Pump Start

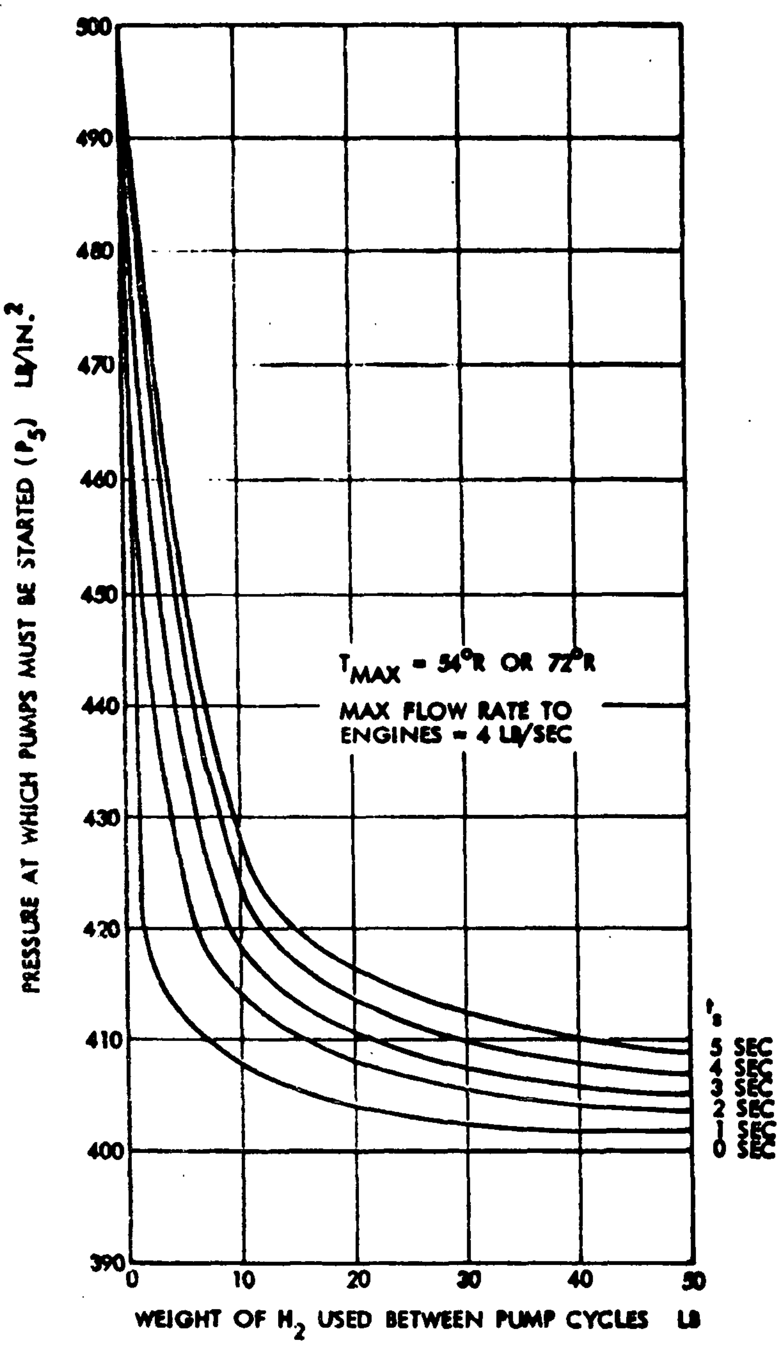


Fig. 9.3-13 LH_2 Accumulator Minimum Pressure Prior to Pump Start

Temperature at state 3 is dependent upon the pump outlet pressure (state 2). This dependence of T 3 on P 2 is shown in Figs. 9.3-14 and 9.3-15.

The storable feed system energy, which does not need to be extracted by cooling, can now be determined, because this energy is a function of states 2, 3, and 4. The energy source is the heat leak into the feed system. Figures 9.3-16, 9.3-17, and 9.3-18 show the energy storage capability per pumping cycle.

The storable energy in the fluid contained in the accumulator is all the energy that is required to raise the system from state 2 to state 3, plus part of the energy required to raise the system from state 3 to state 4. For the process from state 2 to 3, the energy goes to raise the internal energy of the liquid fluid (LH_2 or LO_2) and the helium plus the work terms. Since the liquid fluid weight in the accumulator is greater at state 3 than at state 4, the total energy that can be absorbed by the system has to be weighted, based upon the fluid weight present at each state. The curves in Figs. 9.3-16, 9.3-17, and 9.3-18 are divided as they are for these reasons. If all the fluid is used after reaching state 3, then the energy absorbed (and needs not to be extracted from the system) corresponds to the Δh and work terms (from state 2 to 3). Based upon the fluid weight in the accumulator at state 3 (which is greater than state 4), plus the fluid in the propellant lines, the parameter "weight of liquid used between pump cycles and during pump start" corresponds to the fluid weight in the accumulator when state 4 is reached. If all the fluid is used after reaching state 4, the energy absorbed (and needs not to be extracted from the system) corresponds to the Δh and work terms (from state 2 to 3), plus the Δh terms (from state 3 to 4), based upon the fluid weight in the accumulator at state 4, plus that in the propellant lines.

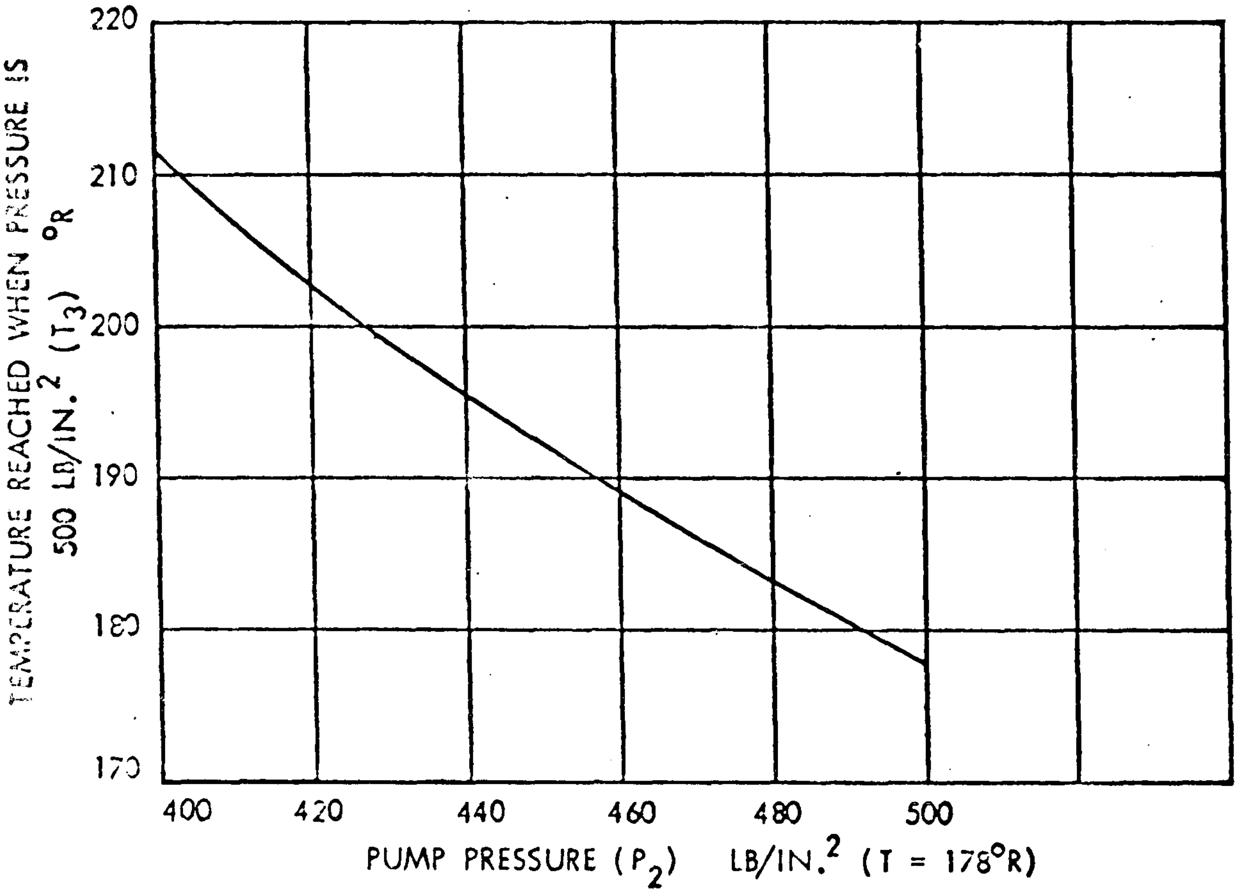


Fig. 9.3-14 Effect of Pump Pressure Setting on Temperature - LO_2

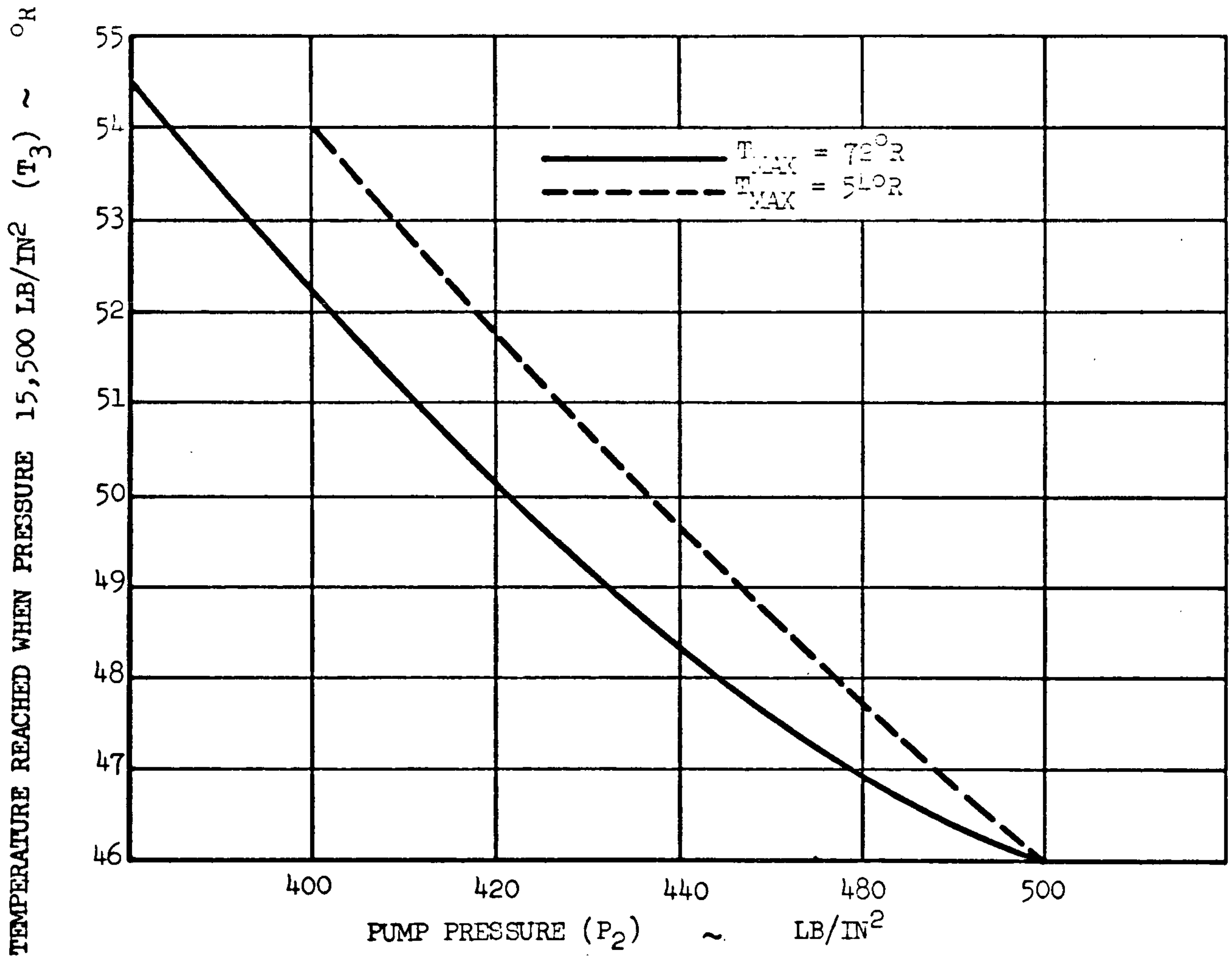


Fig. 9.3-15 Effect of Pump Pressure Setting on Temperature LH_2 (T_{max} = 54^{o}R and T_{max} = 72^{o}R)

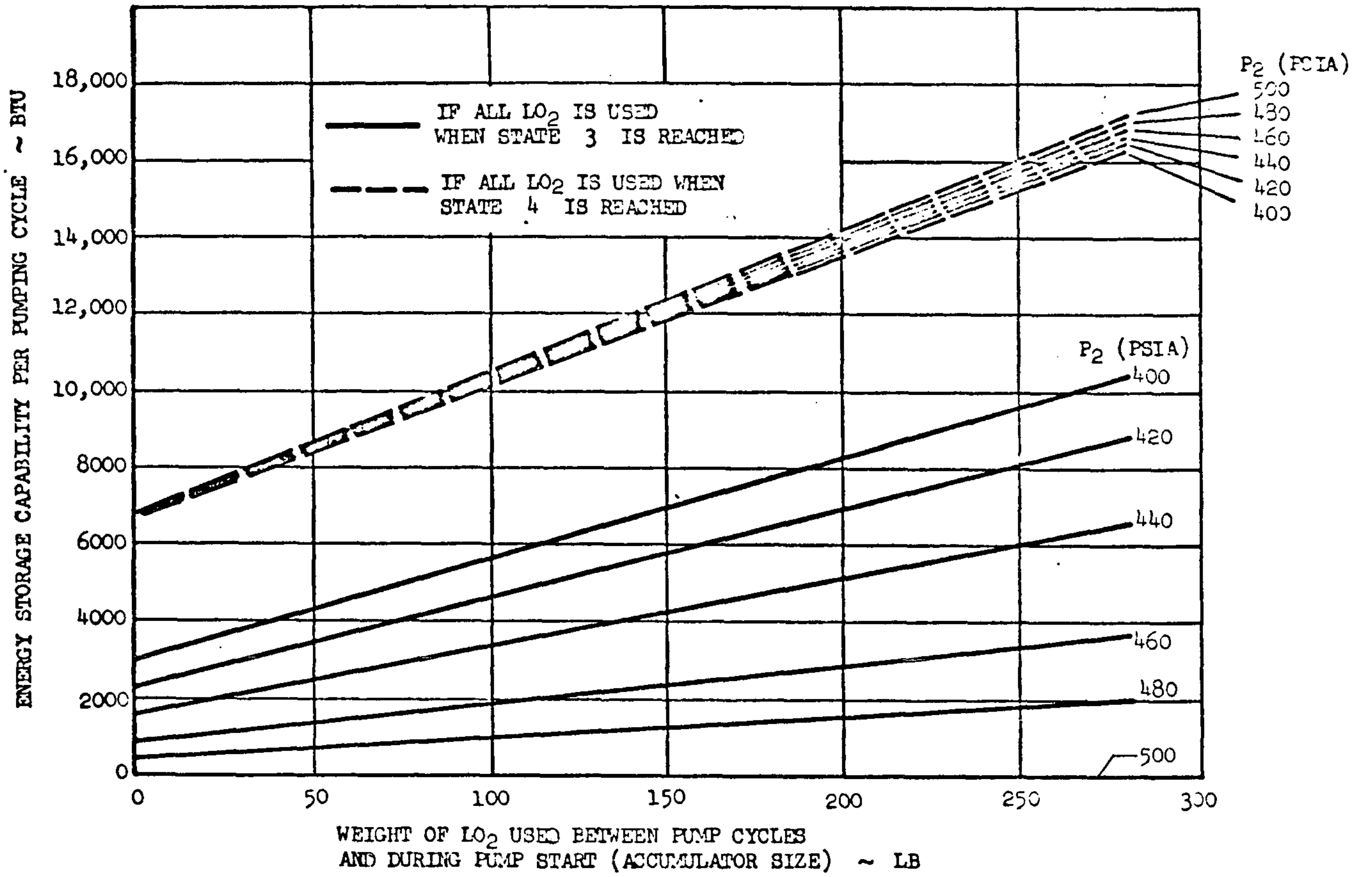


Fig. 9.3-16 Energy Storage Capability - LO_2

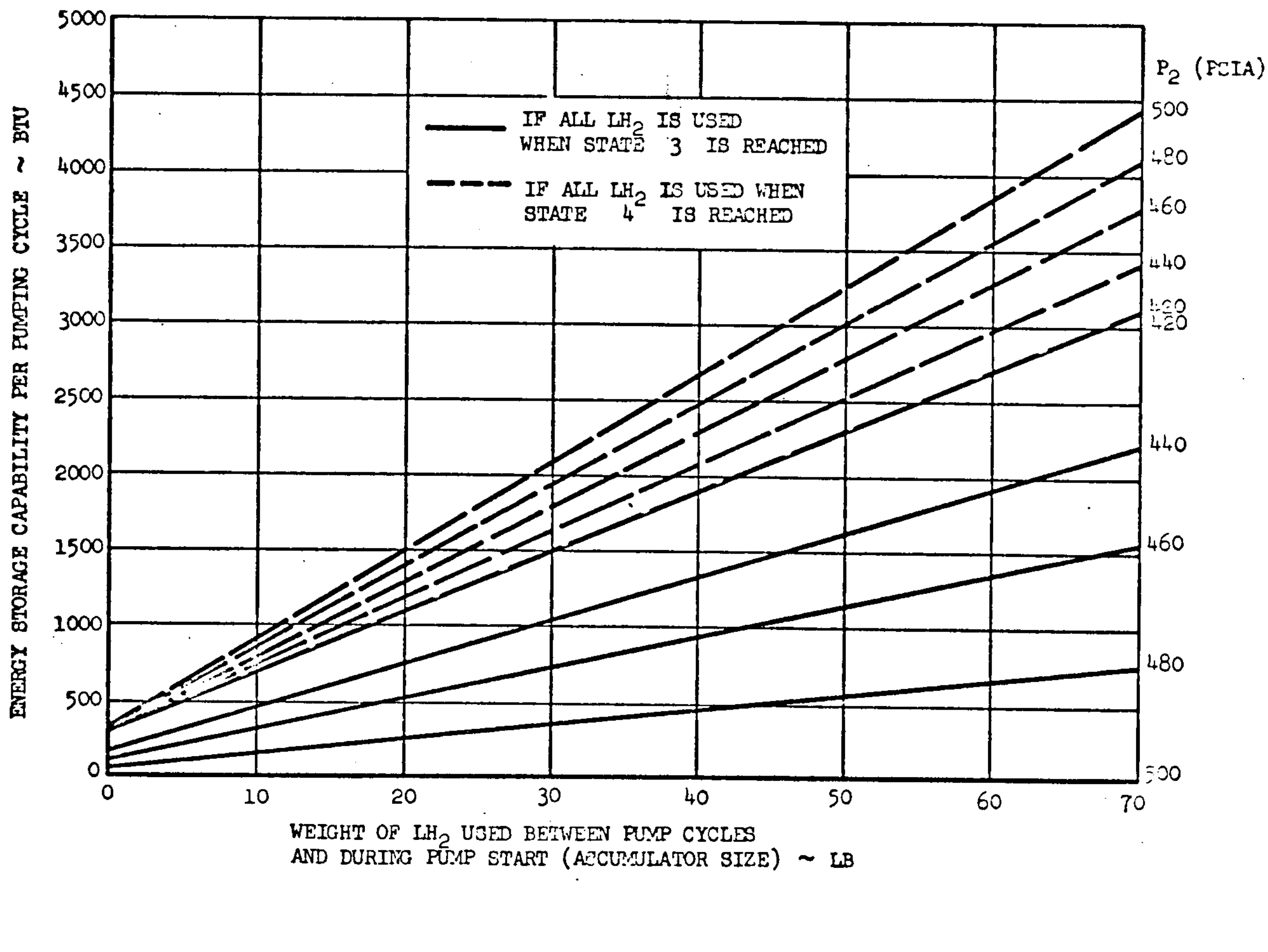


Fig. 9.3-17 Energy Storage Capability - LH_2 ($T_{max} = 54^oR$)

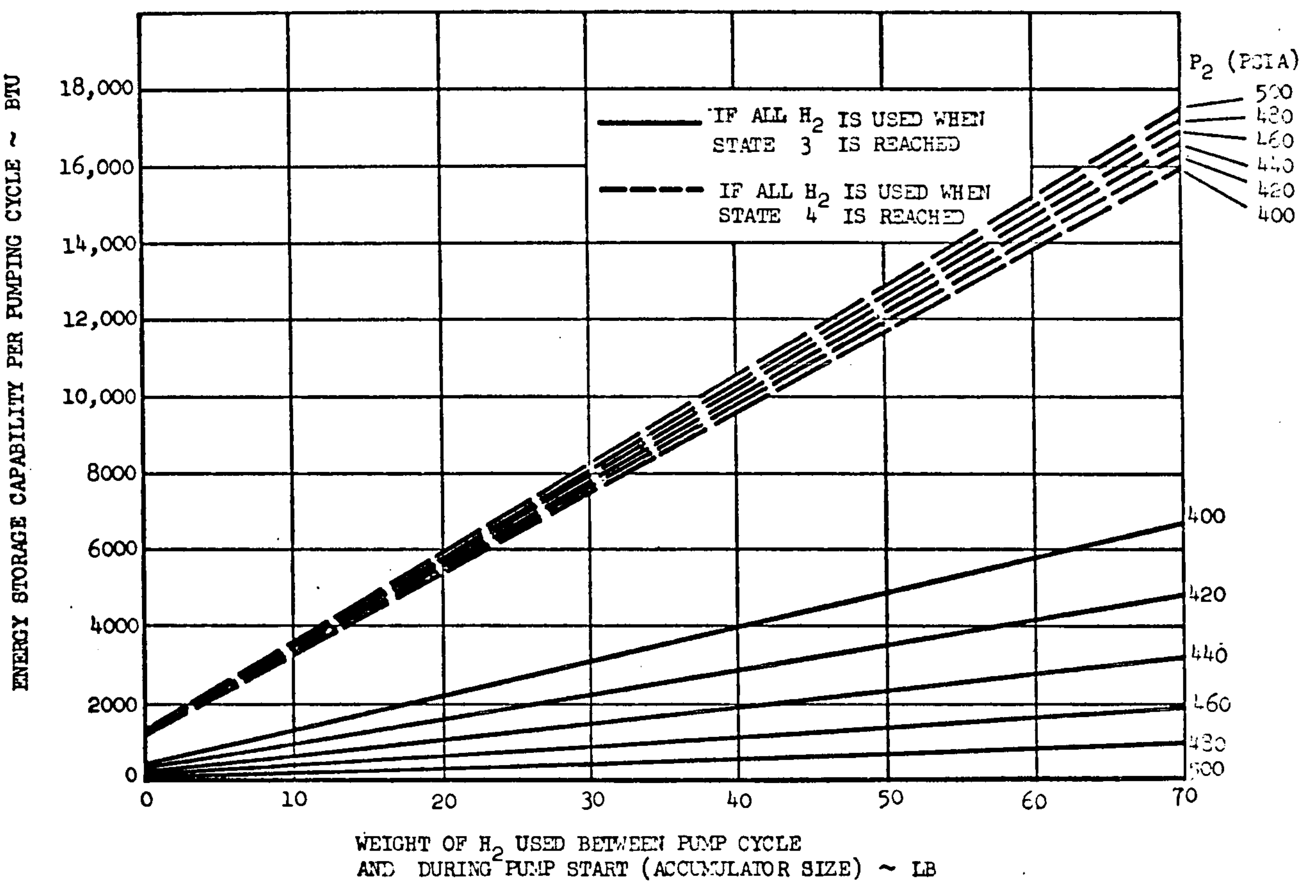


Fig. 9.3-18 Energy Storage Capability - LH_2 (T_{max} = 72°R)

Using the parametric curves generated, a set of typical operating-characteristics can be determined. Table 9.3-2 presents a comparison of the heat leaks into the system with the heat storage capability (based on 25 pumping cycles), using the assumptions shown in the note callouts.

A system weight estimate is shown in Table 9.3-3. The dry weights include the storage tanks (with insulation and vacuum jackets, and propellant acquisition device); components such as valves, pumps, etc., lines (with insulation and vacuum jackets); and helium storage tanks. Dry weight does not include the weights of the engines. Two O_2 accumulators were used and sized such that a total of 80 lb of O_2 plus a 2-sec pump start time O_2 usage were available between pump cycles. Two H_2 accumulators were used and sized such that a total of 20 lb of H_2 plus a 2-sec pump start time H_2 usage were available between pump cycles. The pump pressure setting was 440 psia, the maximum O_2 temperature T 3 was 248°R, and the maximum H_2 temperatures T 3 were 54°R and 72°R. Two accumulator sizing criteria were used: one providing a maximum contraction ratio of 20 percent and the other a maximum contraction ratio of 100 percent. The effect that the contraction ratio has on the accumulator weight is shown in Fig. 9.3-19. The impulse expendables were based on an engine mixture ratio of 4.0 and engine capability of supplying a total impulse of 1,687,000 lb-sec at steady-state conditions (engine I_{sp} = 423 sec) plus 1,018,000 lb-sec at pulsing conditions (engine I_{sp} = 381 sec).

The overall steady-state system I_{sp}, taking into account flow to the engine and gas generators that supply the turbopumps, is estimated to be 420 sec. This is based on an engine I_{sp} of 423 sec and a pump ΔP of 440 lb/in.^{2}. Performance characteristics used for the turbopumps include a pump efficiency of 70 percent and specific propellant consumptions of 2.49 lb/hp-hr for the H_2 turbine and 4.91 lb/hp-hr for the O_2 turbine. These turbopump characteristics result in a system I_{sp} of 3 sec less than the engine-delivered specific impulse.

Table 9.3-2

LIQUID ACPS HEAT LEAK AND COOLING REQUIREMENTS

	O_2 Side	H_2 Side ($T_{max} = 54^{\circ}R$)	H_2 Side ($T_{max} = 72^{\circ}R$)
Heat Leak Rate (Except Turbopump) - Btu/hr	410	600	600
Total Heat Leak for Mission - Btu	69,100	100,800	100,800
Heat Storage Capability (25 cycles) - Btu	178,000*	31,400**	107,800**
Excess Heat to be Extracted - Btu	0	69,400	0
H_2 Required for Cooling (Except Trubopumps) - lb	0	373	0
H_2 Required for Turbopumps		504	
Total H_2 Cooling - Btu (H_2 $T_{max} = 54^{\circ}R/72^{\circ}R$)		877/504	
H_2 and O_2 for Fuel Cell for Heating Turbine - lb		90	

* Based on accumulators sized to hold 80 lb plus 2-sec pump start (112 lb) of O_2, 25 complete cycles, $P_2 = 440$ lb/in.^{2}, averaged between states 3 and 4, as shown in Fig. 9.3-16.

** Based on accumulators sized to hold 20 lb plus 2-sec pump start (28 lb) of H_2, 25 complete cycles, $P_2 = 440$ lb/in.^{2}, averaged between states 3 and 4, as shown in Figs. 9.3-17 and 9.3-18.

Table 9.3-3

LIQUID ACPS WEIGHT SUMMARY (USING TURBOPUMPS)

Component	20 Percent Contraction Ratio H_2 (54°)	(72°R)	100 Percent Contraction Ratio H_2 (54°R)	H_2 (72°R)
H_2 Storage Tank & Insulation	221	221	221	221
H_2 Storage Tank Vacuum Jacket	246	246	246	246
O_2 Storage Tank & Insulation	70	70	70	70
O_2 Storage Tank Vacuum	46	46	46	46
Components, Valves, Pumps	580	580	580	580
Lines & Insulation	88	88	88	88
Line Vacuum Jacket	844	844	844	844
H_2 Accumulators*	881	2500	431	705
O_2 Accumulators*	490	490	207	207
He Tank for H_2 Storage Tank	37	37	37	37
He Tank for O_2 Storage Tank	6	6	6	6
H_2 Storage Tank Acquis. Device	61	61	61	61
O_2 Storage Tank Acquis. Device	10	10	10	10
Total Dry Weight	3580	5199	2847	3121
Residuals				
H_2 in H_2 Storage Tank	73	73	73	73
H_2 in Lines	12	12	12	12
H_2 in H_2 Accumulators	3	3	3	3
O_2 in O_2 Storage Tank	40	40	40	40
O_2 in Lines	210	210	210	210
O_2 in O_2 Accumulators	20	20	20	20
He in H_2 Storage Tank	19	19	19	19
He in O_2 Storage Tank	83	110	83	110
He in O_2 Storage Tank	3	3	3	3
He in O_2 Accumulators	6	6	6	6
Total Residuals	469	496	469	496
Expended Wgt.				
H_2 Impulse Propellant	1330	1330	1330	1330
O_2 Impulse Propellant	5320	5320	5320	5320
H_2 for Conditioning (Pumps)	26	26	26	26
O_2 for Conditioning (Pumps)	26	26	26	26
H_2 for Cooling	877	504	877	504
H_2 & O_2 for Fuel Cells	90	90	90	90
Total Expended Weight	7669	7296	7669	7269
Total System Weight	11,718	12,991	10,985	10,913

* (Including He sphere where needed)

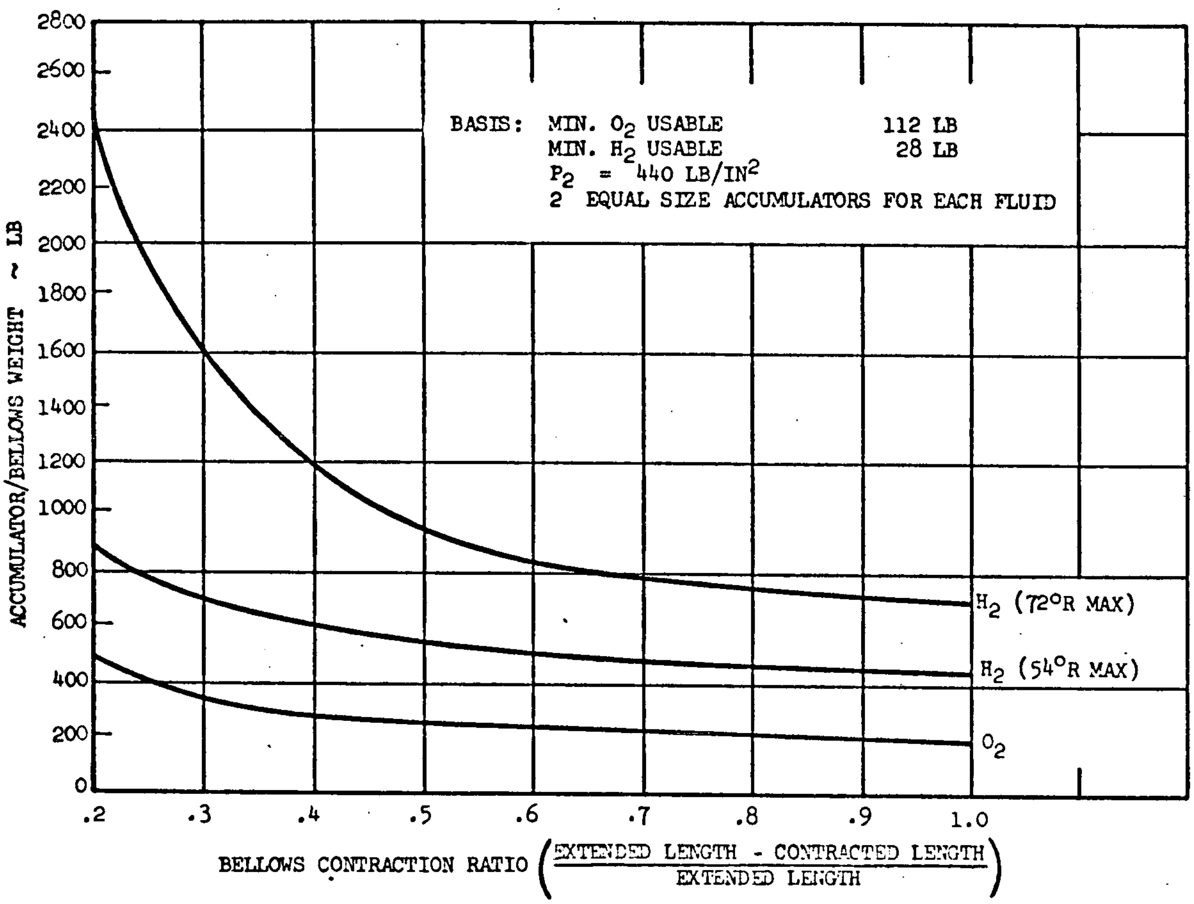


Fig. 9.3-19 Effect of Bellows Contraction Ratio on Accumulator/Bellows Weight

9.3.2.1.2 Electric-Motor Driven Pumps. Use of cryogenically cooled electric-motor-driven pumps for the ACPS was considered and the weight compared to the turbopump concept given above. The corresponding weight changes are shown in Table 9.3-4. Two cases were considered for this concept and include: (1) using three APU generators, each sized to supply full-power demands of the electric motors; and (2) using four APU generators, each sized to supply 50 percent of full-power demands of the electric motors. When only three generators are installed, a total of 200-percent power redundancy is required; however, when four generators are installed only 100-percent power redundancy is required. Consequently, the generators are smaller in size and result in weight savings.

9.3.2.2. Supercritical Subsystem. Analyses and sensitivity studies were necessary to examine the storage conditions and the thruster chamber pressure requirements. This information was necessary before the tradeoff studies could be performed.

9.3.2.2.1. ACPS Supercritical Storage Analyses and Sensitivity Studies. These analyses were performed to examine the supercritical storage of hydrogen and oxygen for the ACPS subsystem. From the ACPS technology studies, the range of supply temperatures to the thrusters was selected as follows:

- Hydrogen: 250 $^{\circ}$R to 350 $^{\circ}$R
- Oxygen: 350 $^{\circ}$R to 500 $^{\circ}$R

As a basis for comparison, a propellant loading of 5,000 lb. was selected.

Results of the hydrogen supercritical storage analyses are presented in Fig. 9.3-20. As noted, the optimum storage pressure was found to be 600 psi, and the lower the delivery temperature, the lower the storage weight.

Table 9.3-4

CHANGES TO WEIGHT BREAKDOWN FOR ELECTRIC MOTOR DRIVEN PUMPS (USING ON-BOARD APU TO RUN ELECTRIC GENERATORS)

	3 Generator Case *	4 Generator Case **
Delete 3 O_2 Turbines	-51.0	-51.0
Add 3 O_2 Motors	+65.1	+65.1
Delete 3 H_2 Turbines	-51.0	-51.0
Add 3 H_2 Motors	+258.3	+258.3
Delete On-Board APU Generator	-60.0	-60.0
Add 3 or 4 Generators (at 240 hp or 180 hp ea)	+504.0	+336.0
Change in Dry Weight	+665.4	+497.4
Delete H_2 + O_2 to Drive Turbopump	-52.0	-52.0
Add H_2 + O_2 to Drive APU	+38.5	38.5
Delete H_2 Cooling of Turbopumps	-504.0	-504.0
Delete H_2 + O_2 for Fuel Cells	-90.0	-90.0
Change in Expended Weight	-607.5	-607.5
Net Change	+57.9 lb	-110.1 lb

* 1 out of the 3 APU/generators must operate (each generator sized for full flow)
**2 out of the 4 APU/generators must operate (each generator sized for half flow)

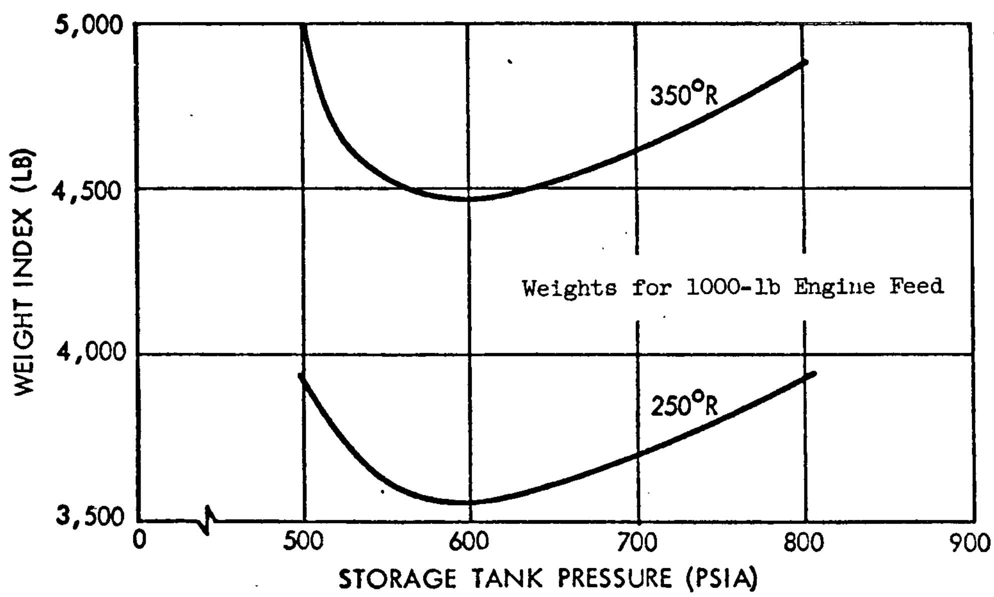


Fig. 9.3-20 ACPS LH_2 Propellant - Optimization of Supercritical Storage Pressure

The results of the oxygen supercritical storage analyses are presented in Fig. 9.3-22. Storage weights did not reach an optimum value, since oxygen is limited by the temperature and pressure to remain in the supercritical region (absolute minimum 700 psia). The minimum storage tank pressure was selected to be 900 psia, since the supercritical storage must deliver high flowrates without any possibilities of developing two phase conditions.

A tabulation of the supercritical storage weights at the optimum points for the curves presented is shown in Table 9.3-5.

Table 9.3-5

TABULATION OF SUPERCRITICAL STORAGE ANALYSES RESULTS

	H_2 System		O_2 System	
Engine Feed Temperature, $^{\circ}R$	250	350	350	500
Engine Feed Pressure, psia	450	450	450	450
Storage Tank Pressure, psia	600	600	900	900
Engine Propellant Wt, lb	1,000	1,000	4,000	4,000
Conditioning Propellant Wt, lb	205	337	94	150
Storage Tank Residual, lb	100	76	265	207
Accumulator Residual, lb	25	25	23	23
Total Propellant, lb	1,330	1,438	4,382	4,380
Storage Tank Wt, lb	1,732	2,230	607	677
Accumulator Wt, lb	401	648	34	80

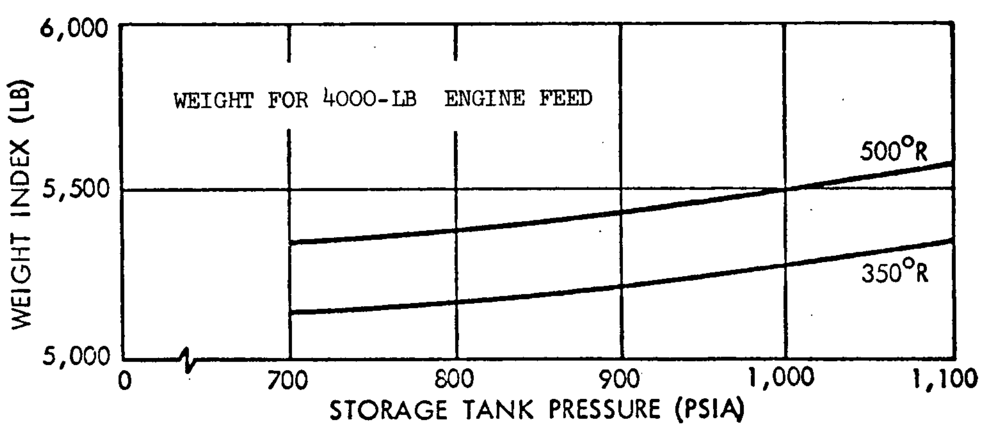


Fig. 9.3-21 ACPS LO_2 Propellants - Optimization of Supercritical Storage Pressure

9.3.2.2.2 <u>Determination of Thruster Chamber Pressures for Supercritical ACPS Subsystems.</u> The technology contracts for the ACPS subsystems have shown that for the concepts with subcritical storage (gas/gas thrusters), the optimum chamber pressure range is approximately 300 to 500 psia. Analyses were made to determine the optimum chamber pressure for thrusters used with supercritical supply systems. The variables considered in these analyses were thruster chamber pressure, propellant storage temperature, and propellant storage pressure. Analyses were based on the use of thirty 1850-lb thrusters having unit weights of 71 lb at 100-psia chamber pressure, 42 lb at 200-psia chamber pressure, and 31 lb at 300-psia chamber pressure. Storage tank sizes were based on 1,000 lb of H_2 and 4,000 lb of O_2 for delivery to the thrusters, loaded initially as a slightly subcooled liquid. The accumulator sizes were based on a 2-sec supply of propellant at average flowrates of 4.2 lb per sec of H_2 and 11.7 lb per sec of O_2.

Supercritical H_2 storage at 250°R and 350°R and over a range of storage pressures to 800 psia was investigated. Supercritical O_2 storage was investigated at 350°R and 500°R and over a range of storage pressures to 1,100 psia.

The H_2 system weight was found to be a minimum at 600-psia storage pressure, and to be significantly lower at 250°R storage temperature. The O_2 system weight was found to be lower at 350°R storage temperature and to optimize with respect to storage pressure at some point below supercritical; the optimum point was, therefore, taken as 850 to 900 psia storage pressure to assure supercritical conditions. The system weights were plotted against storage pressure as shown in Fig. 9.3-22.

Using the determined optimum storage temperatures, the analysis was repeated, allowing tank blowdown to pressures corresponding to the assumed engine chamber pressures of 100, 200, and 300 psia. For this purpose, final tank pressure was assumed to be 150 psia above the chamber pressure. Results are shown in Fig. 9.3-23 as a function of chamber pressure. The optimum occurs at approximately 225-psia chamber pressure.

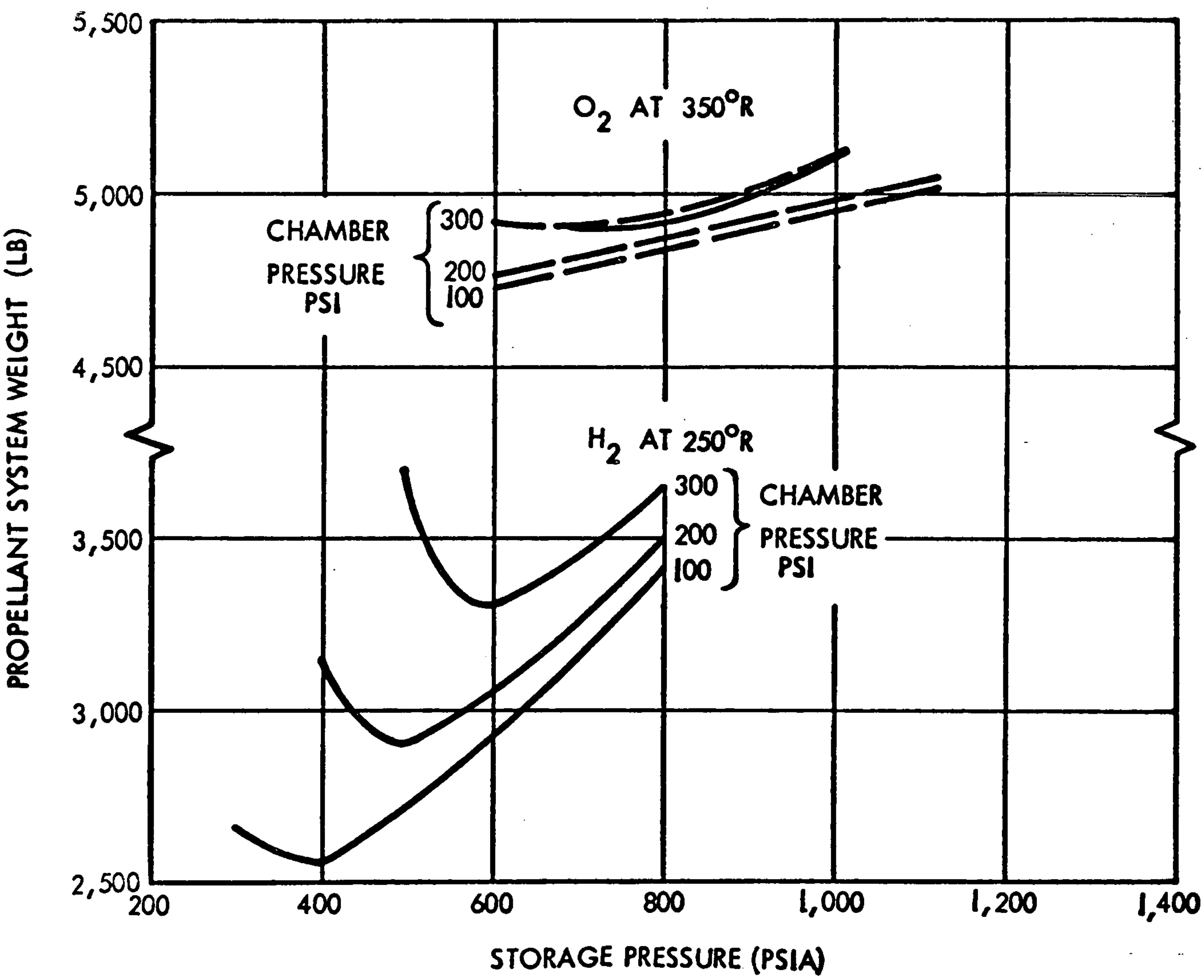


Fig. 9.3-22 System Weight Vs Storage Pressure

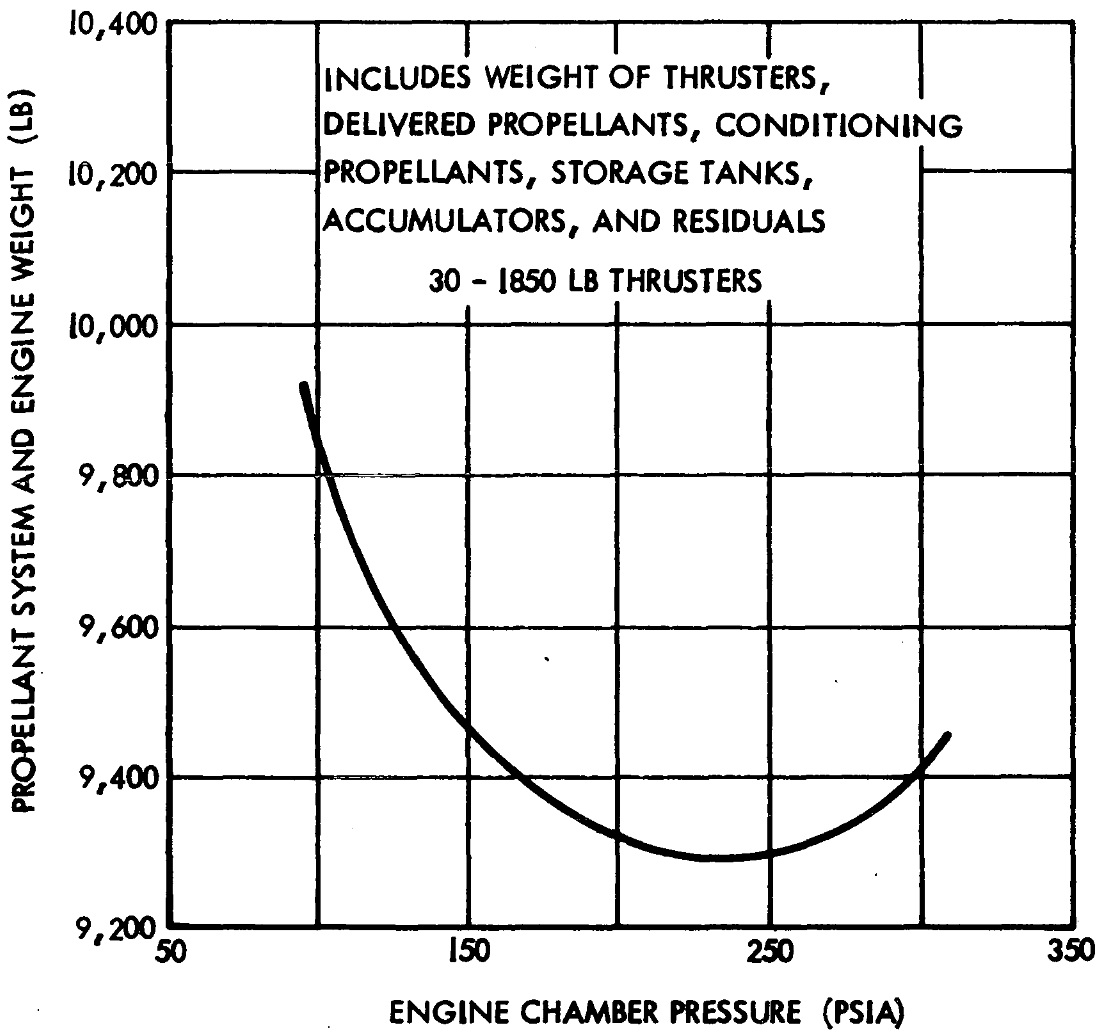


Fig. 9.3-23 ACPS Weight Vs Engine Chamber Pressure-Supercritical Propellant Storage System

9.3.2.3 Turbopump Chilldown and Cooling. Turbopump chilldown and cooling analyses were performed to evaluate technology study results. The principal considerations in the analyses were:

- Pump must be maintained at a temperature to allow restart with immediate introduction of liquid.

- Turbine must be maintained at temperature above $600^{\circ}R$ for repeated restarts. For this study, temperature was held at $900^{\circ}R$.

- Cooling hydrogen flow must remove heat input to the pump to maintain the temperature at the permissible value for restart.

9.3.2.3.1 Permissible Pump Temperature for Restart. From Reference 9-4, it is concluded that pump temperature "superheat" above the liquid-boiling point may affect start as follows, relative to liquid flow into the pump during restart:

- $30^{\circ}R$ "Superheat" - zero boilout during start
- $50^{\circ}R$ "Superheat" - gradual boilout
- $75^{\circ}R$ "Superheat" - rapid boilout; unreliable restart

On the basis of the aforementioned, it will be assumed that the hydrogen-pump impeller may be at a temperature of $40^{\circ} + 50^{\circ} = 90^{\circ}R$, at pump start, and that the oxygen-pump impeller may be at a temperature of $172^{\circ} + 50^{\circ} = 222^{\circ}R$.

<u>Turbopump Model</u>. The turbopump model was taken from the TRW Systems

"Space Shuttle High Pressure Auxiliary Propulsion Subsystem Definition," NAS 9-11013.

and from AiResearch data inputs. Figure 9.3-24 shows the LH_2 turbopump model. The LO_2 turbopump is assumed to be a two-stage centrifugal pump, driven by a one-stage turbine.

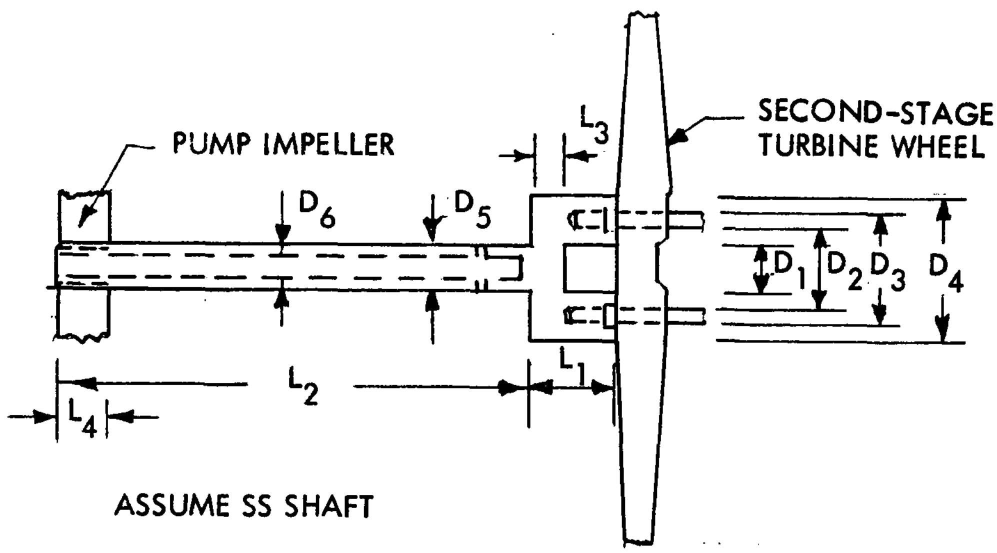
The assumed turbine inlet temperature is 2200°R and the outlet temperature is 1100°R. After shutdown, at the maximum possible heat removal rate, the turbine would require 5 to 7 hours to cool to 900°R. (The turbine may be insulated so that heat is transferred to the pump or may be left open to radiate heat.) In order to prevent transfer to the pump, the heat can be removed with a maximum flowrate of 3 lb/hr of hydrogen. After the turbine temperature reaches 900°R, the required flowrate drops to 0.6 lb/hr.

It is expected that one turbopump will be operated as much as 75 to 100 times per mission, one will operate approximately 25 times per mission; and another will be a standby. With these assumptions, and considering the weight-averaging of the heat-removal requirements, the coolant estimates are:

<u>For 168-hour mission:</u>

(1) Maximum coolant required for pump operating 75 to 100 times = 350-400 lb/mission

Two-Stage, Axial Flow Impulse Turbine
Two-Stage Centrifugal Pump



	D_1	D_2	D_3	D_4	D_5	D_6	L_1	L_2	L_3	L_4
Dimension, in.	1.14	1.33	2.39	2.62	1.18	0.68	0.87	6.4	0.30	0.76

First-stage tip diameter	= 8.66 in.	Turbine
Second-stage tip diameter	= 9.41 in.	

Pump tip diameter = 7.45 in.
Pump hub diameter = 3.10 in.

Fig. 9.3-24 LH_2 Turbopump Model

(2) Coolant required for pump operating 25 times = 250-300 lb/mission

(3) Minimum coolant required for pump on standby = 100 lb/mission

(4) Total coolant flow = 700 to 800 lb/mission.

9.3.2.4 Propellant Acquisition. Propellant acquisition devices are essential for the Attitude Control Propellant Supply for either the integrated or nonintegrated systems. Acquisition of propellant in all axes is required.

In this study, the acquisition method considered to be most satisfactory was the use of the "gallery" principle with inlets containing multiple screens. Multiple screens are considered to be necessary to provide the retention capability for the accelerations and liquid head pressures established in the requirements. The utility of multiple screens was recently established by LMSC.

These propellant acquisition devices are of general application to several subsystems. The analyses and designs are presented in Appendix B.

9.3.3 Attitude Control Propellant Supply Tradeoff Studies

These studies included:

- Comparison of supercritical and subcritical subsystems
- Comparison of turbopumps and electric-motordriven pumps
- Comparison of liquid/liquid and gas/gas subystems

9.3.3.1 Supercritical Versus Subcritical Comparison. A comparison was made of the supercritical and subcritical ACPSs. (See Table 9.3-6.) Note that the principal weight difference is from the heavy storage tanks in the supercritical supply.

Table 9.3-6

COMPARISON OF SUBCRITICAL AND SUPERCRITICAL STORAGE
FOR ATTITUDE CONTROL PROPELLANT SUPPLY

Subsystem	Subcritical Storage	Supercritical Storage
Fill/Vent		
• Components	109	108
• Lines	104	104
Storage and Feed		
• Valves and Controls	369	328
• Lines	6	6
• Propellant Tanks	448 (180)*	3,956 (3,720)*
• Tank Insulation	51	44
• Accumulators	1,035	413
Pressurization		
• Components	90	198
• Pressurant Storage Spheres	44	-
• Lines	5	5
Propellant Conditioning		
• Turbopumps	213	-
• Heat Exchanger	109	225
• Acquisition Device	100	-
Subsystem Dry Weight	2,683 (2,415)*	5,387 (5,151)*
Impulse O_2	5,230	5,230
Impulse H_2	1,310	1,310
Conditioning O_2	495	662
Conditioning H_2	495	662
Pump Cooling H_2	504	-
Tank Cooling H_2	42	-
Residual O_2	57	312
Residual H_2	23	164
Loaded O_2	5,782	6,204
Loaded H_2	2,374	2,136
Loaded He	33	-
Total Fluids	8,189	8,340
Total System Weight	10,872 (10,604)*	13,727 (13,491)*

*Numbers in parenthesis indicate nonvacuum jacketed tanks.

The supercritical tanks require a high-heat addition to maintain tank pressure for the high withdrawal rates. This requires external heat exchangers with gas generators to supply the required heating rates. The advantages of the supercritical subsystem are:

- Elimination of the turbopumps
- Elimination of the propellant acquisition requirements.

Each of these advantages reduce development cost.

9.3.3.2 Comparison of Turbopump and Electric-Motor-Driven Pumps. A study was performed to compare pumping techniques for the ACPS. Turbopumps were compared with various techniques utilizing cryogenically cooled electric-motor-driven pumps. The basic requirement was to supply sufficient propellant at the appropriate pressure to operate four ACPS engines after a double failure. Resulting flowrates and pressures to accomplish the above requirements are as follows:

- Hydrogen flowrate of 3.80 lb/sec at a minimum pressure of 1043 psia
- Oxygen flowrate of 14.81 lb/sec at a minimum pressure of 940 psia

Table 9.3-7 shows the weight comparison results. The turbopump case weight is based on installing three sets of pumps - each pump set-sized to deliver the total flowrates required so that sufficient flow is available after two failures. Included in the turbopump weight are the estimated O_2 and H_2 weights which are required to maintain the turbopump at a temperature to assure instant-start capability. The two numbers given for cooling and heating the turbopump represent the estimated range of these requirements.

The electric-motor-driven pump concepts considered included: (1) using the existing on-board Auxiliary Power Unit (APU), but replacing the generator portion with a larger generator in order to meet the electric-power demands of the electric motor, and (2) using a separate turbine/generator, which

Table 9.3-6

Comparison of Turbopumps and Pumps with Electric Motors

TURBOPUMP CONCEPT(S)			THREE INSTALLED SETS*		FOUR INSTALLED SETS**	
			USING ONBOARD APUs	USING SEPARATE APU TURBINE/GENERATOR	USING ONBOARD APUs	USING SEPARATE APU TURBINE/GENERATOR
COMPONENT	WT	COMPONENT	WT	WT	WT	WT
H_2 TURBOPUMP (3) ($\dot{\omega}$ = 3.80-LB/SEC AT 1043-PSIA ΔP EACH)	75	H_2 PUMPS (3.80 LB/SEC AT 1043-PSI ΔP EACH)	69.0	69.0	64.0	64.0
O_2 TURBOPUMP (3) ($\dot{\omega}$ = 14.81 LB/SEC AT 940-PSIA ΔP EACH)	124	O_2 PUMPS (14.81 LB/SEC AT 940-PSI ΔP EACH)	10.0	10.0	9.0	9.0
H_2 AND O_2 FOR COOLING AND HEATING	125/595	H_2 PUMP MOTORS O_2 PUMP MOTORS	546.0 119.0	546.0 119.0	364.0 75.0	364.0 75.0
H_2 AND O_2 FOR DRIVING TURBINES (500-SEC DURATION)	85	GENERATOR WEIGHT (3 AT 360 Kw) DELETE GENERATOR ON APU	774.0 -60.0	774.0 0	516.0 -60	516.0 0

*1 OUT OF 3 MUST OPERATE (EACH SET SIZED FOR FULL FLOW)
**2 OUT OF 4 MUST OPERATE (EACH SET SIZED FOR HALF FLOW)

supplies the electric power for the motors only. Two cases were considered for each of these concepts; they include:

a. Installing three sets of pumps, each pump set-sized to deliver the total flowrate

b. Installing four sets of pumps - each pump set-sized to deliver one-half the total flowrate.

Both of these cases have sufficient flow after any two failures.

When only three pump sets are installed, a total of 200-percent power redundancy is required; however, when four pump sets are installed, only 100-percent power redundancy is required. As a consequence, the motors, pumps, and generators are smaller in size and result in about a 450-to-500 lb weight savings over the case where three pump sets are installed.

9.3.3.3 Comparison of the Liquid/Liquid and Gas/Gas ACPS. The extent of the ACPS evaluations provided a number of comparisons between the Liquid/Liquid and Gas/Gas ACPS subsystems. A summary comparison is presented in Table 9.3-8. As may be seen from these results, the comparisons are very sensitive to the bellows contraction ratios, the liquid temperatures, and the pump-drive approach. The Liquid/Liquid ACPS subsystems can be designed to have comparable weights to the Gas/Gas ACPS. Attractive features of the Liquid/Liquid ACPS subsystem are:

- Pump start transient may be less severe.
- Heat exchanger development is not required.

Table 9.3-8

COMPARISON OF LIQUID/LIQUID AND GAS/GAS ATTITUDE CONTROL PROPELLANT SUPPLY

TYPE OF STORAGE	TYPE OF FEED	TYPE OF PUMP DRIVE	NO. OF GENS.	ACCUAT. BELLOWS CONTRACT. RATIO (%)	MAX H_2 TEMP (°R)	DRY WEIGHT (LB)	TOTAL SYSTEM WEIGHT (LB)
SUBCRIT	GAS	TURBINE	–	–	–	3,009	11,198
SUPERCRIT	GAS	–	–	–	–	5,713	14,053
SUBCRIT	LIQUID	TURBINE	–	20	54	3,580	11,718
SUBCRIT	LIQUID	TURBINE	–	20	72	5,199	12,991
SUBCRIT	LIQUID	TURBINE	–	100	54	2,847	10,985
SUBCRIT	LIQUID	TURBINE	–	100	72	3,121	10,913
SUBCRIT	LIQUID	MOTOR	3	20	54	4,245	11,776
SUBCRIT	LIQUID	MOTOR	3	20	72	5,864	13,049
SUBCRIT	LIQUID	MOTOR	3	100	54	3,512	11,043
SUBCRIT	LIQUID	MOTOR	3	100	72	3,786	10,971
SUBCRIT	LIQUID	MOTOR	4	20	54	4,077	11,608
SUBCRIT	LIQUID	MOTOR	4	20	72	5,696	12,881
SUBCRIT	LIQUID	MOTOR	4	100	54	3,344	10,875
SUBCRIT	LIQUID	MOTOR	4	100	72	3,618	10,803

9.4 AUXILIARY POWER UNIT (APU) SUPPLY

The Auxiliary Power Unit (APU) Supply subsystem evaluation required extensive consideration of the duty-cycle and flow-rate requirements to the APUs. Therefore, it was necessary to compile a considerable quantity of data from the LMSC technology contracts that were in progress. These were:

- "Auxiliary Power Unit Technology", NAS 3-14408, AiResearch Manufacturing Company
- "Auxiliary Power Unit Technology", NAS 3-14407, Rocketdyne Division of North American Rockwell

Then, differences in these data were resolved and generalized requirements were developed.

The principal tradeoff in the APU Supply was between the employment of subcritical and supercritical storage concepts. The approaches to evaluate are presented in Fig. 9.4-1.

9.4.1 Selection of Candidate Subsystems

In the selection of candidate subsystems, consideration was given to arriving at generalized supply subsystems which would not be dependent upon heat availability from the hydraulic, lubrication, or alternator subsystems. Also, it was considered desirable to select the concepts so that they were not wholly dependent upon APU exhaust and the aforementioned cooling functions. Considerations associated with the concepts are presented in Figs. 9.4-2, 9.4-3, and 9.4-4.

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9.4.1.1 Schematics for Components Evaluations at AiResearch. Auxiliary Power Unit Supply schematics (Appendix E) were prepared and submitted to AiResearch for the selection of components. The schematics were formulated to represent the possible component arrangements presented in Figs. 9.4-2, -3, and -4. Also, these schematics were used to perform the initial redundancy analyses employing the SETA II computer program. The identified redundancies, presented in Appendix E, established the least-reliable components in the subsystems.

9.4.1.2 Schematics for Sensitivity and Tradeoff Studies. Detailed schematics were prepared for the APU Supply sensitivity and tradeoff studies. The schematics were iterated several times, as the safety criteria were examined, and the instrumentation and control analyses were performed. The concepts are discussed in the following paragraphs.

9.4.1.2.1 Subcritical APU Supply Subsystem. The Subcritical APU Supply subsystem concept used in the evaluations is shown in Fig. 9.4-5. This subsystem employs pumps to provide pressure. Since the APU will be running when the pump is running, it appears logical to drive the pump with an electrical motor. Accumulators are employed to start the APUs.

A separate gas-generator-supplied heat exchanger is used to condition the reactants to the storage conditions. The propellants are heated to a higher temperature (dependent upon the oxidizer-to-fuel ratio) prior to entering the gas generator of the APUs. This last heat addition utilizes the exhaust gases from the APUs.

The tanks are helium-pressurized to provide (1) a continuous-start capability and (2) the zero-gravity start prior to reentry. This zero-gravity start requires an all-axes propellant-acquisition device.

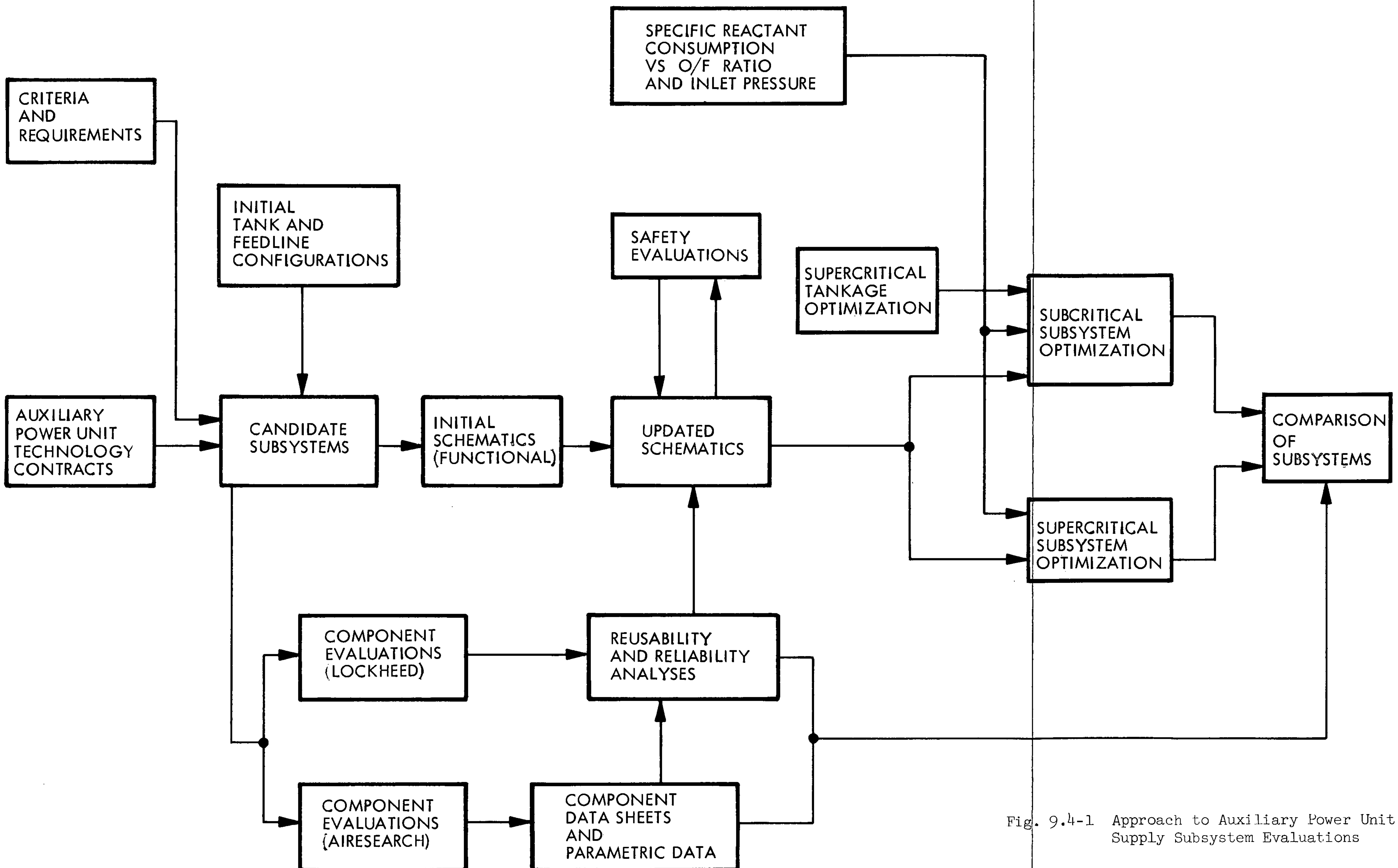

Fig. 9.4-1 Approach to Auxiliary Power Unit Supply Subsystem Evaluations

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FOLDOUT FRAME 2

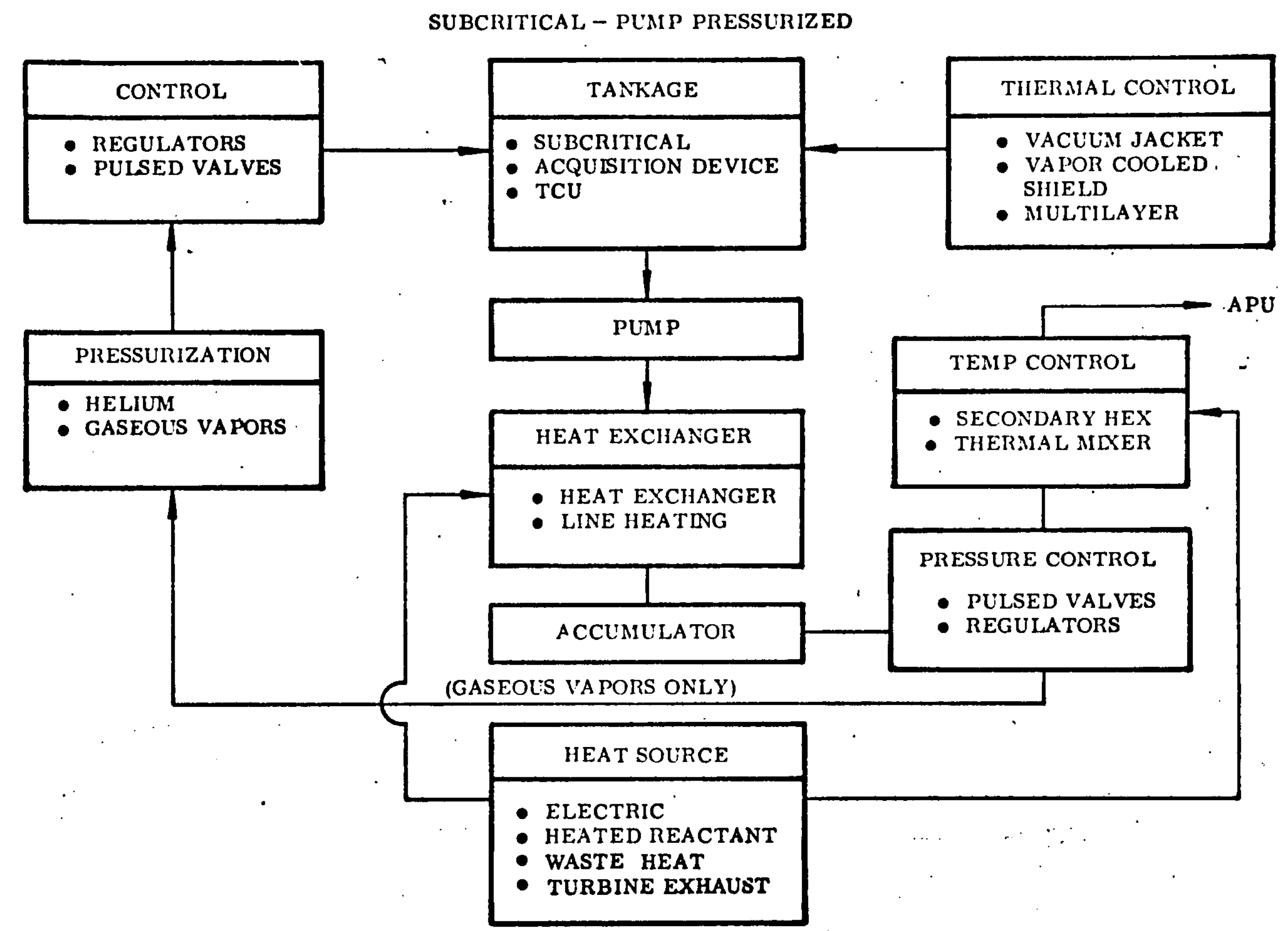

Fig. 9.4-2 APU Supply System

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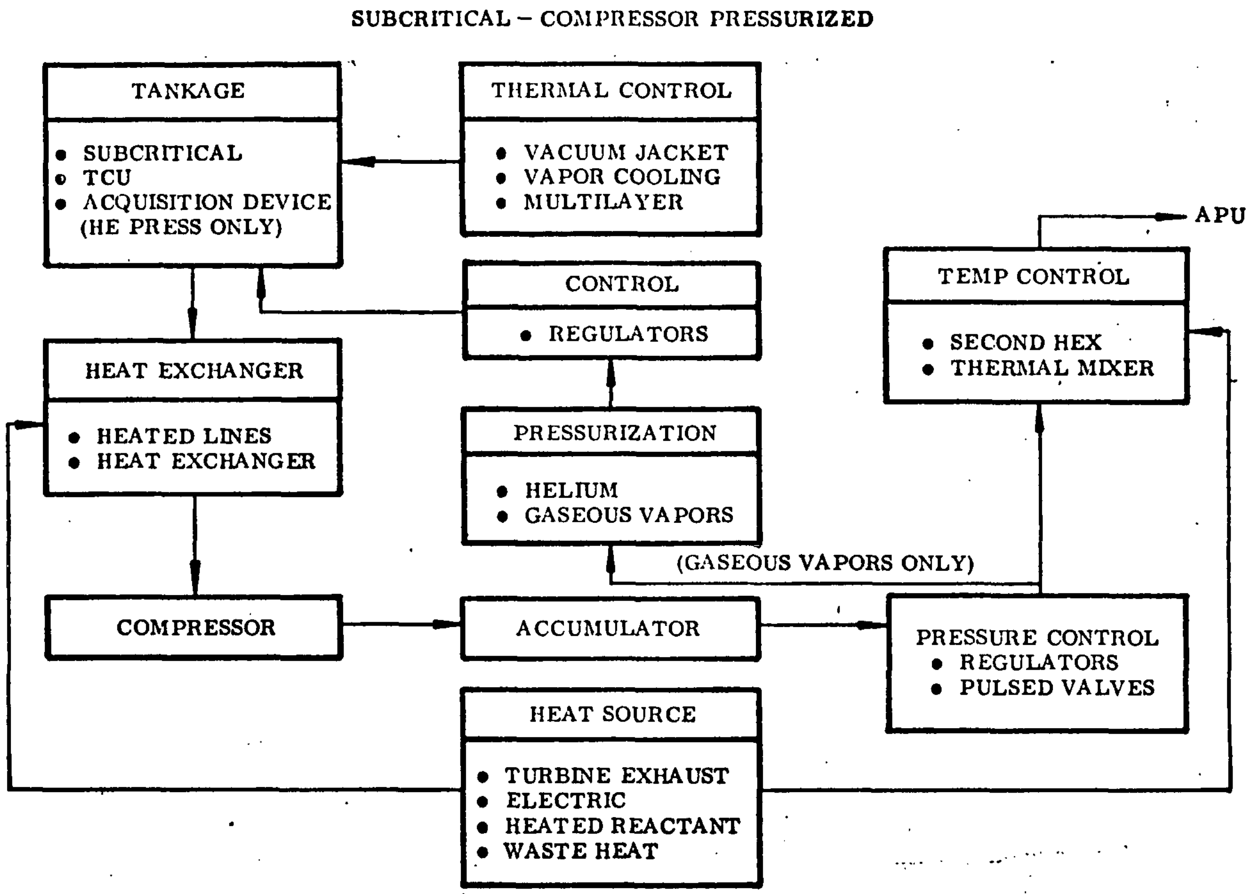

Fig. 9.4-3 APU Supply System

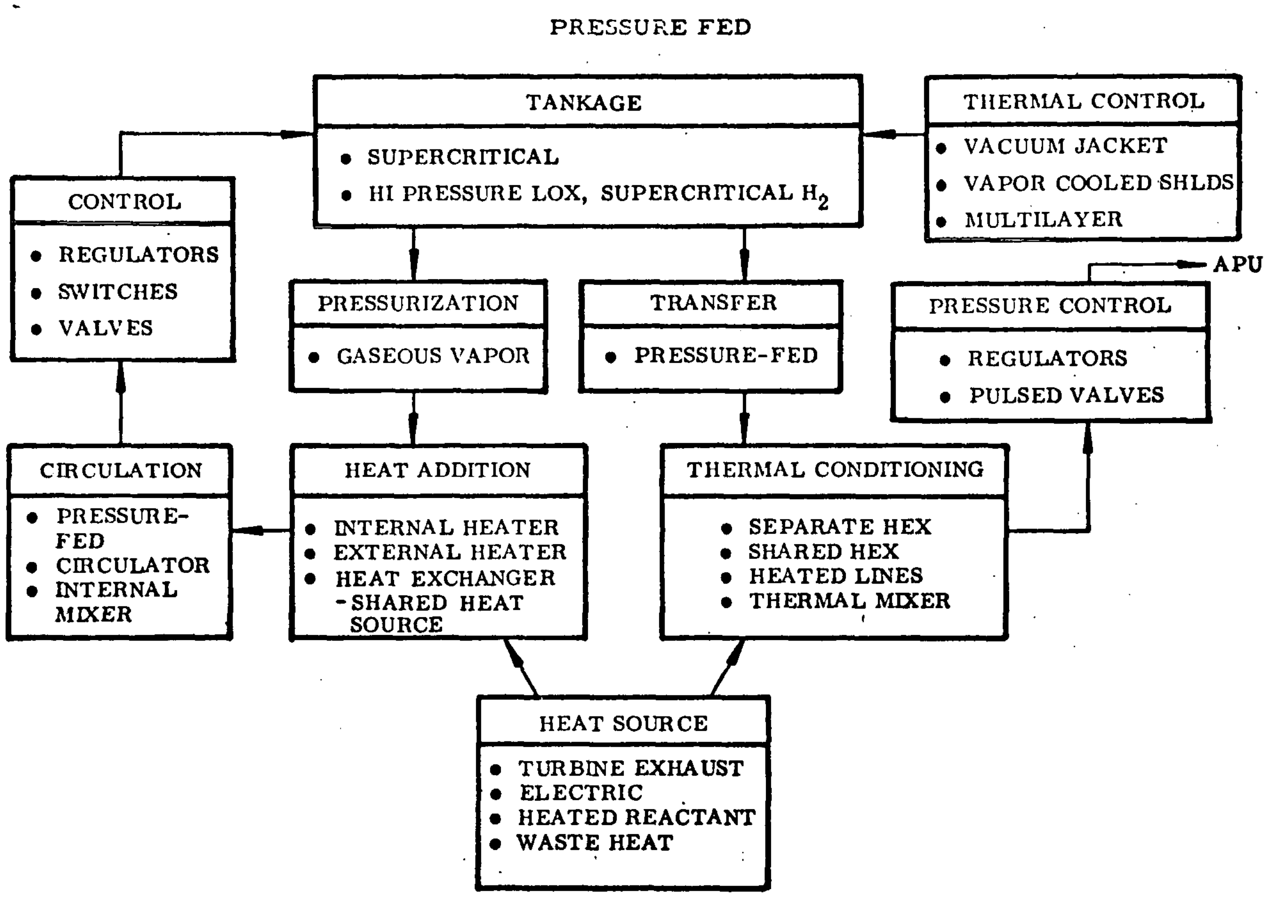

Fig. 9.4-4 APU Supply System

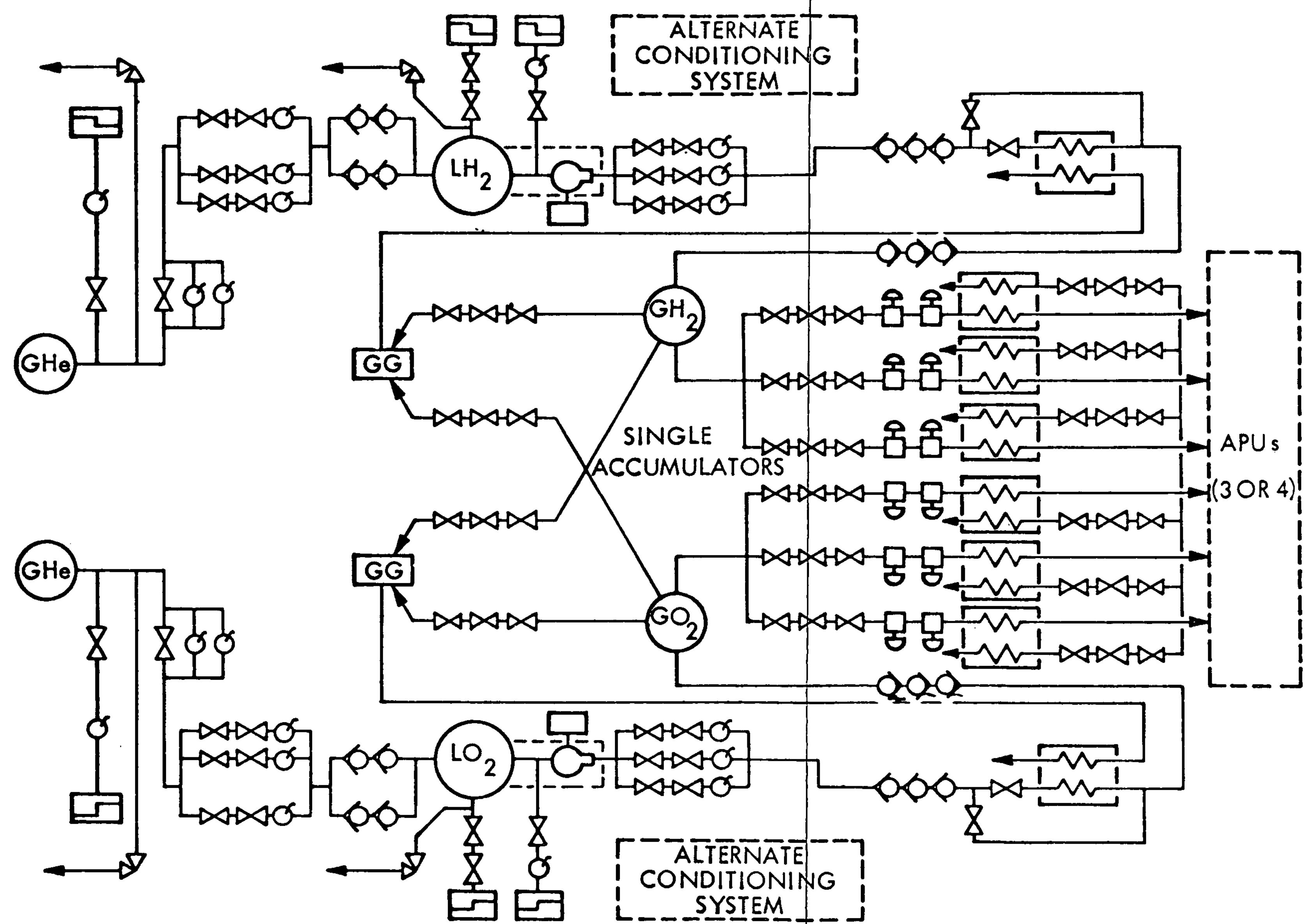

Fig. 9.4-5 Subcritical APU Supply

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9.4.1.2.2 Supercritical APU Supply Subsystem. The Supercritical APU Supply subsystem (Fig. 9.4-6) is somewhat similar to the subcritical supply subsystem. Reactants are conditioned to keep the pressure at the desired level in the storage tanks through the use of external heat exchangers with recirculation compressors. The reactants are conditioned to the storage temperature by the use of a heat exchanger heated with a gas generator or with APU exhaust. Final conditioning of the reactants is with turbine exhaust to achieve the necessary temperature as determined by the oxidizer-to-fuel ratio.

9.4.2 Detailed Subsystem Analyses and Sensitivity Studies

Analyses and sensitivity studies are presented in this subsection, and the tradeoff studies are presented in subsection 9.4.3.

9.4.2.1 Mixture Ratio and Temperature Relationships for the APUs. The required APU Supply conditioning is the major concern in the evaluations. The effect of inlet temperature is illustrated in Fig. 9.4-7. Rocketdyne and AiResearch data, which resulted from the initial phases of the referenced technology contracts, are shown. Note that the mixture ratio is inversely proportional to the inlet temperature.

Relationships between specific reactant consumption and mixture ratio are presented in Fig. 9.4-8. Observe that the specific reactant consumption increases with increased mixture ratio. However, there is definitely a tradeoff regarding storage and conditioning as compared to the O/F ratio.

Analysis showed insufficient turbine-exhaust temperature to meet the external heating requirements at altitude with a mixture ratio of 0.5, based on heat-exchanger effectiveness of 0.80.

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9.4.2.2 Supercritical Supply Storage Optimization. The analyses and sensitivity studies were performed to determine the effects of storage temperature and storage pressure. Because of the sensitivity of the specific reactant consumption, the percent of full flow, and the mixture ratio, the following conditions were examined:

a. Two APU sizes to produce 850-hp total output

- Three APUs - each operating with maximum possible power of 450-hp
- Two APUs - each operating with maximum power of 850-hp

b. Mixture ratios:

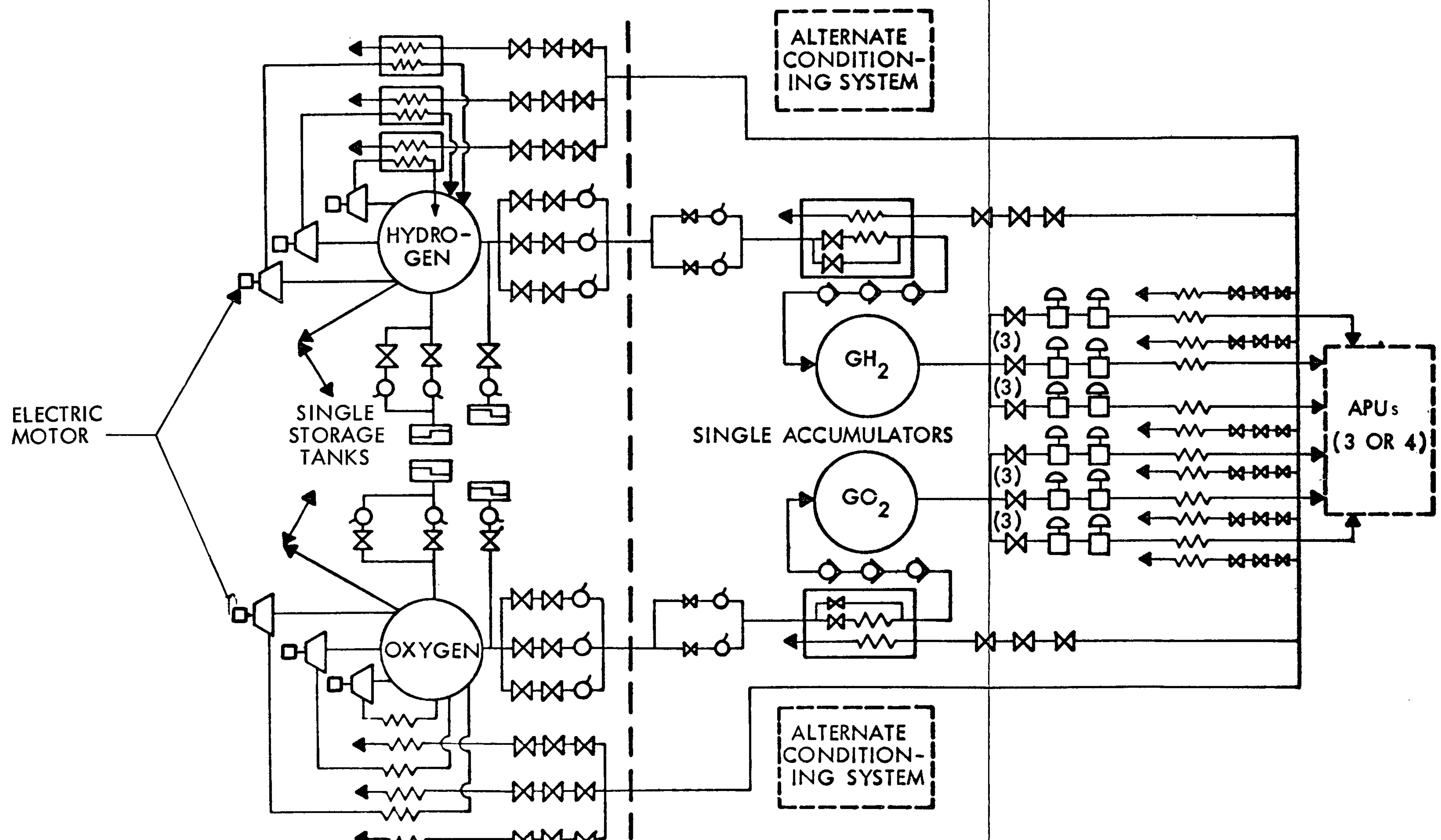
- O/F of 0.5
- O/F of 0.9

Weight factors considered were:

- Hydrogen or oxygen
- Storage tanks
- Accumulators
- Residuals
- Conditioning reactant quantity.

The results of the hydrogen analyses are presented in Figs. 9.4-9 through 9.4-12. Comparisons of these figures regarding hydrogen indicate the following:

- Minimum H_2 system weight occurs at minimum APU pressure and storage temperature. This is caused by high tank-weight sensitivity to pressure and temperature, to the point that system sensitivity to all other factors is overriden.



FOLDOUT FRAME 2

Fig. 9.4-6 Supercritical APU Supply

FOLDOUT FRAME 1

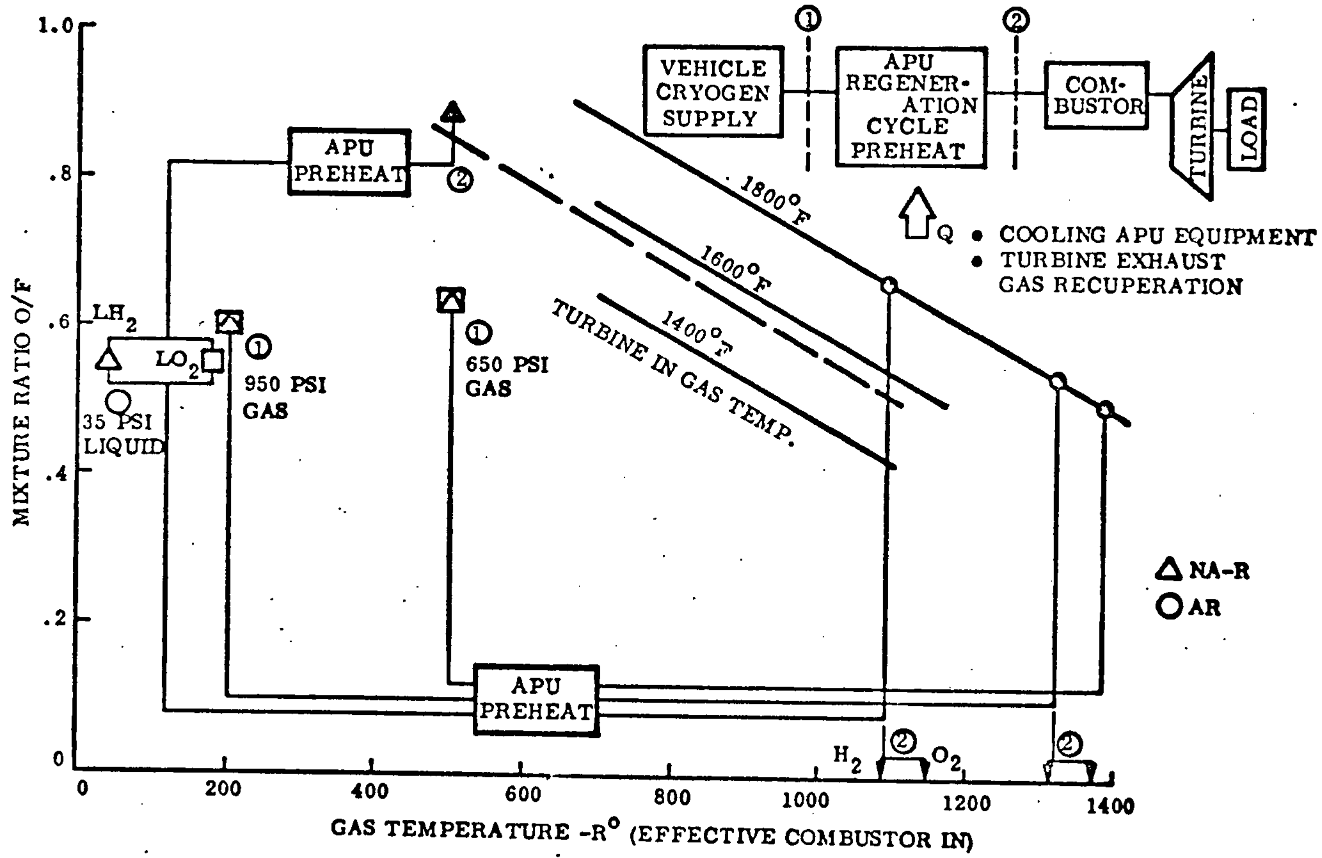


Fig. 9.4-7 Effect of Inlet Gas Temperature on APU Unit O/F Ratio

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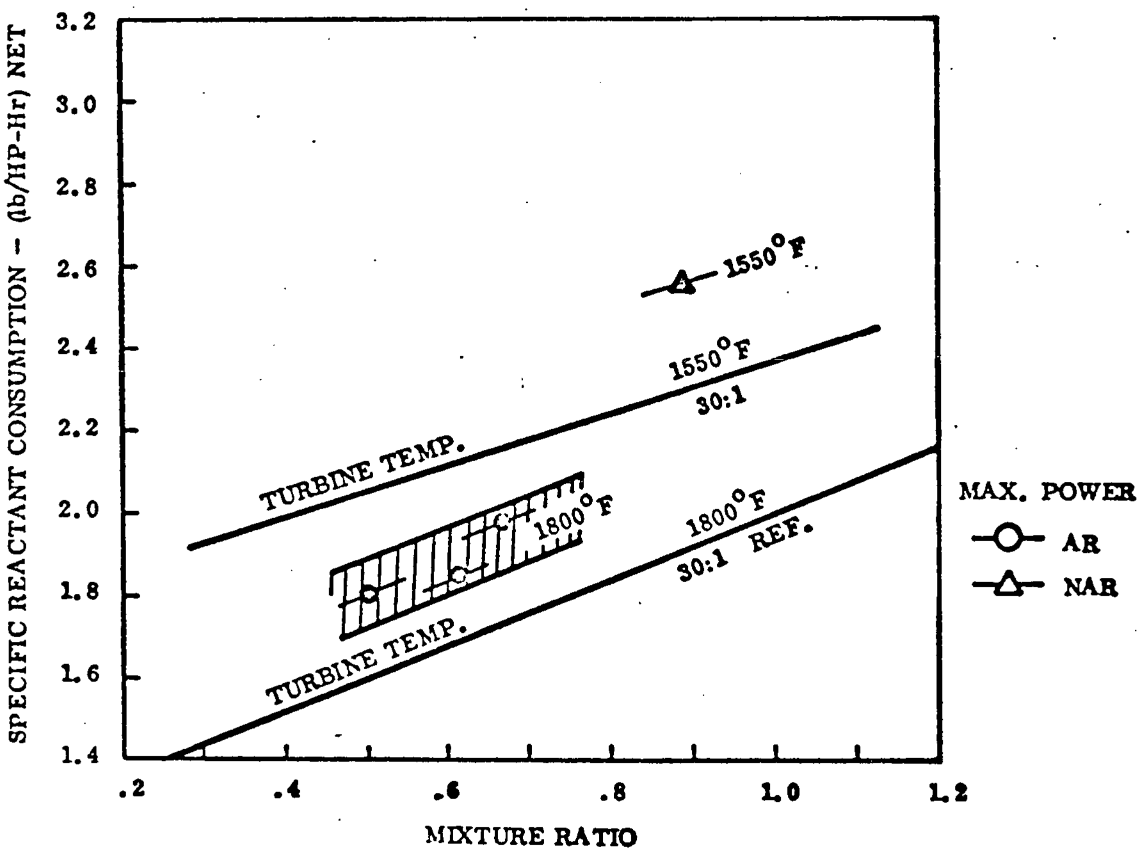

Fig. 9.4-8 Mixture Ratio Effects on Specific Reactant Comsumption

WEIGHT VS STORAGE TEMPERATURE

- 168-Hour Mission
- Three 450-HP APUs Operating
- Mixture Ratio = 0.5
- Storage Pressure = Gas Generator discharge pressure plus 100 psi
- Includes weight of H_2, Storage Tank, Accumulator, Residuals, and Tank Conditioning Quantity

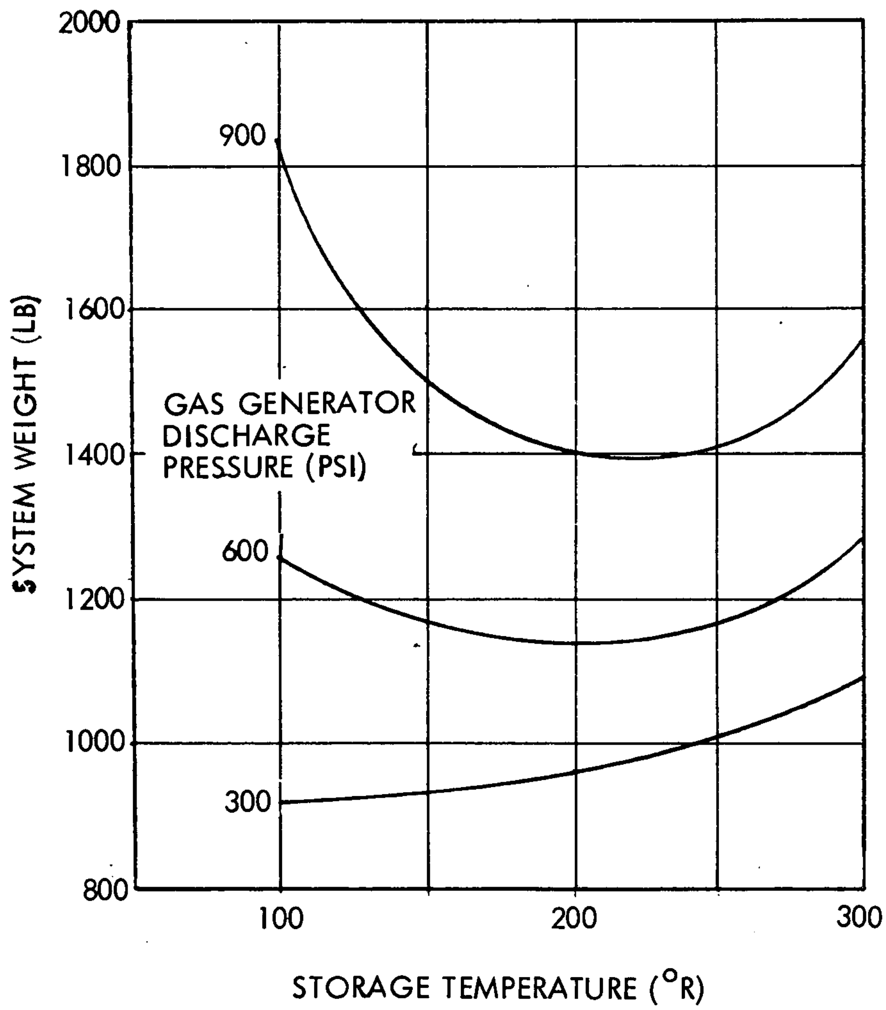

Fig. 9.4-9 APU System Supercritical H_2 Storage System

WEIGHT VS STORAGE TEMPERATURE

- 168-Hour Mission
- Two 850-HP APUs operating
- Mixture Ratio = 0.5
- Storage Pressure = Gas Generator discharge pressure plus 100 psi
- Includes weight of H_2, Storage Tank, Accumulator, Residuals, and Tank-Conditioning Quantity

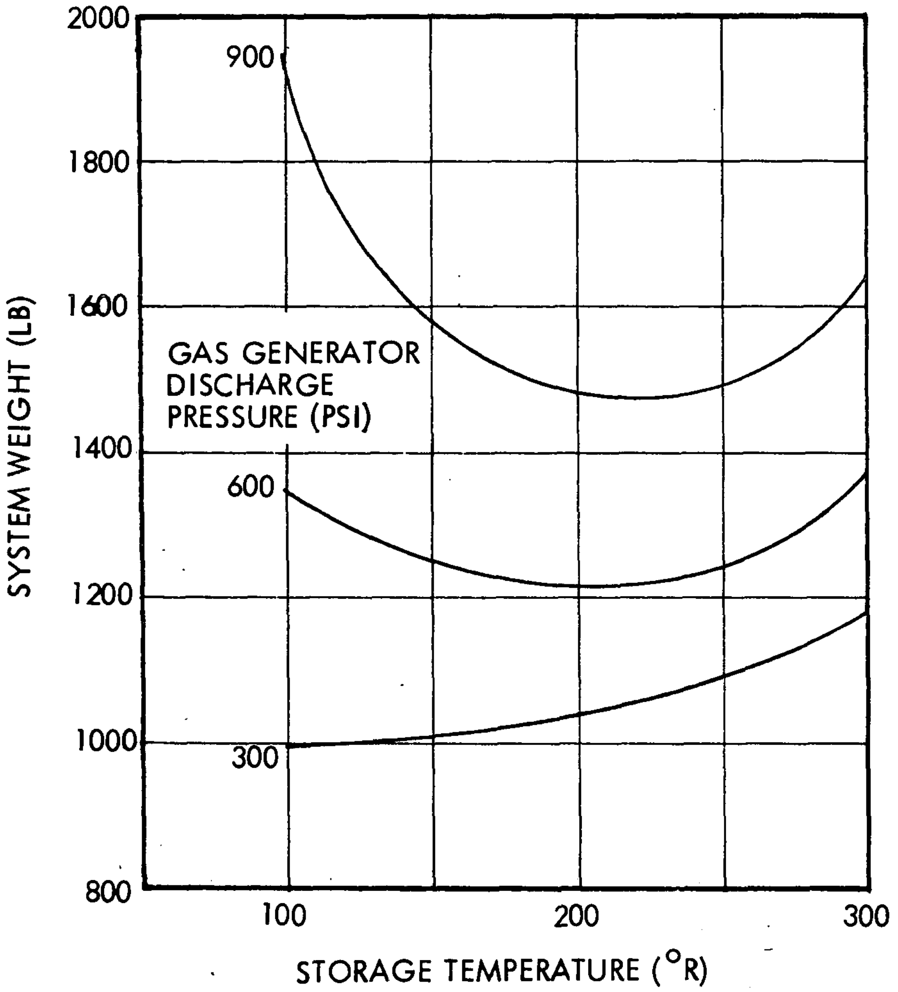

Fig. 9.4-10 APU System Supercritical H_2 Storage System

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WEIGHT VS STORAGE TEMPERATURE

- 168-Hour Mission
- Three 450-HP APUs operating
- Mixture Ratio = 0.9
- Storage Pressure = Gas Generator discharge pressure plus 100 psi
- Includes weight of H_2, Storage Tank, Accumulator, Residuals, and Tank-Conditioning Quantity

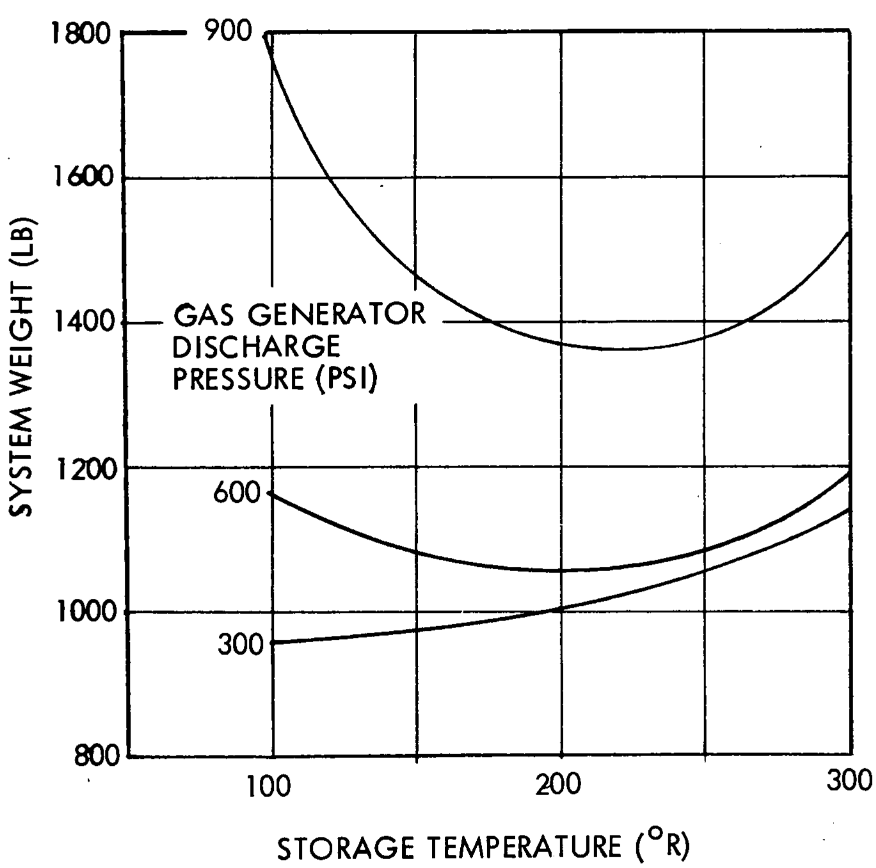

Fig. 9.4-11 APU System Supercritical H_2 Storage System

WEIGHT VS STORAGE TEMPERATURE

- 168-Hour Mission
- Two 850-HP APUs operating
- Mixture Ratio = 0.9
- Storage Pressure = Gas Generator discharge pressure plus 100 psi
- Includes weight of H_2, Storage Tank, Accumulator, Residuals, and Tank-Conditioning Quantity

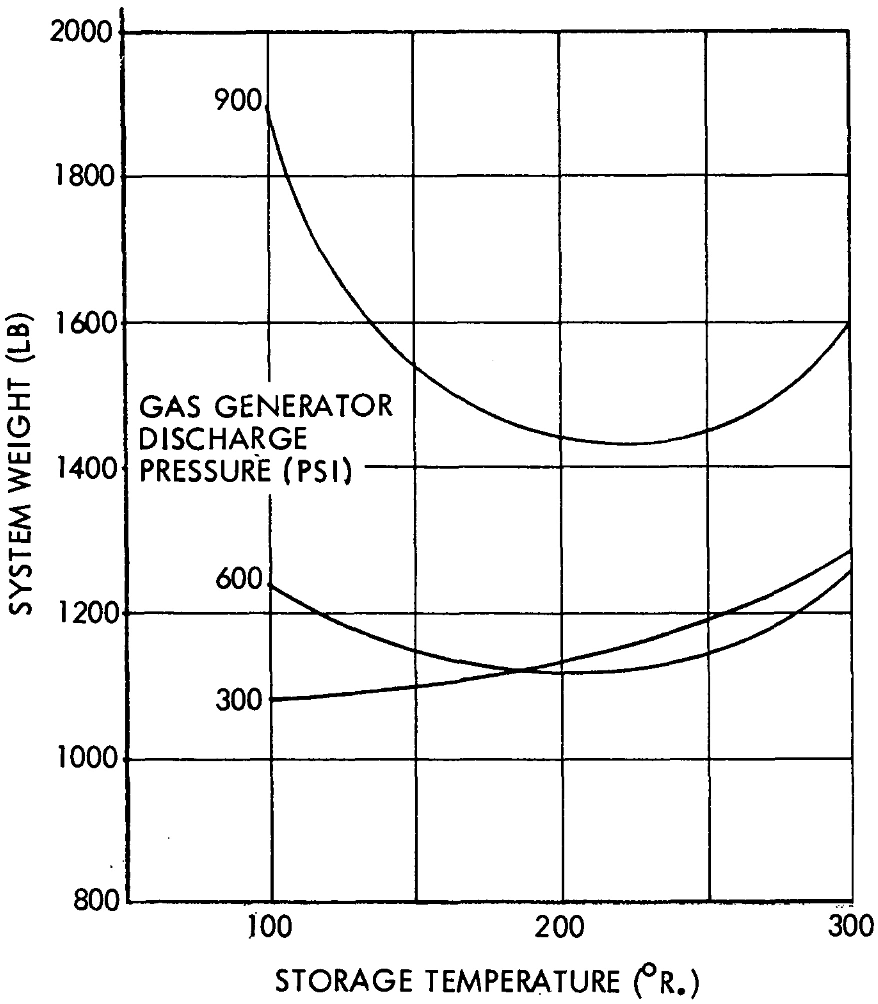

Fig. 9.4-12 APU System Supercritical H_2 Storage System

- Lower H_2 system-weight results for the case of three 450-hp units than for two 850-hp units. This is because, at the higher load factor, which results with the three 450-hp units, a lower specific reactant consumption results.

- Lower H_2 system-weight results for the 300-psi APU pressure with a mixture ratio of 0.5 than with 0.9, due to higher SRC with M/R = 0.9. The SRCs at 600 psi and 900 psi are also higher at M/R = 0.9, but by a smaller margin, so that the increase of SRC for those pressures is offset by the reduction in H_2 flow due to the higher mixture ratio.

Oxygen results are presented in Figs. 9.4-13 and 9.4-14. The following sensitivities are observed in these data.

- Lower O_2 system-weight occurs with M/R = 0.5 than with M/R = 0.9, for all storage conditions and both APU sizes. The smaller storage-tank volume and weight required for the O_2 does not override the sensitivity of the system to the M/R effect.

- Lower O_2 system-weight occurs with the three 450-hp APUs because of higher load factor and lower SRC.

- Minimum O_2 system-weight occurs with maximum APU pressure and the highest storage temperature. The system sensitivity to the combined effects of lower SRC and lower residual propellant overrides the increase of tank weight due to higher pressure.

9.4.2.3 Propellant Acquisition Analyses. The type of acquisition device required for the Auxiliary Power Unit Supply is the same as that for the Attitude Control Propulsion Supply. This device must allow a zero-gravity start or attitude control accelerations in any direction. The device must either be stable

WEIGHT VS. STORAGE TEMPERATURE

- 168-HOUR MISSION
- THREE 450-HP UNITS OPERATING
- OPTIMUM STORAGE PRESSURE
- INCLUDES WEIGHT OF STORAGE TANK, ACCUMULATOR, RESIDUALS, AND DELIVERED AND CONDITIONING O_2

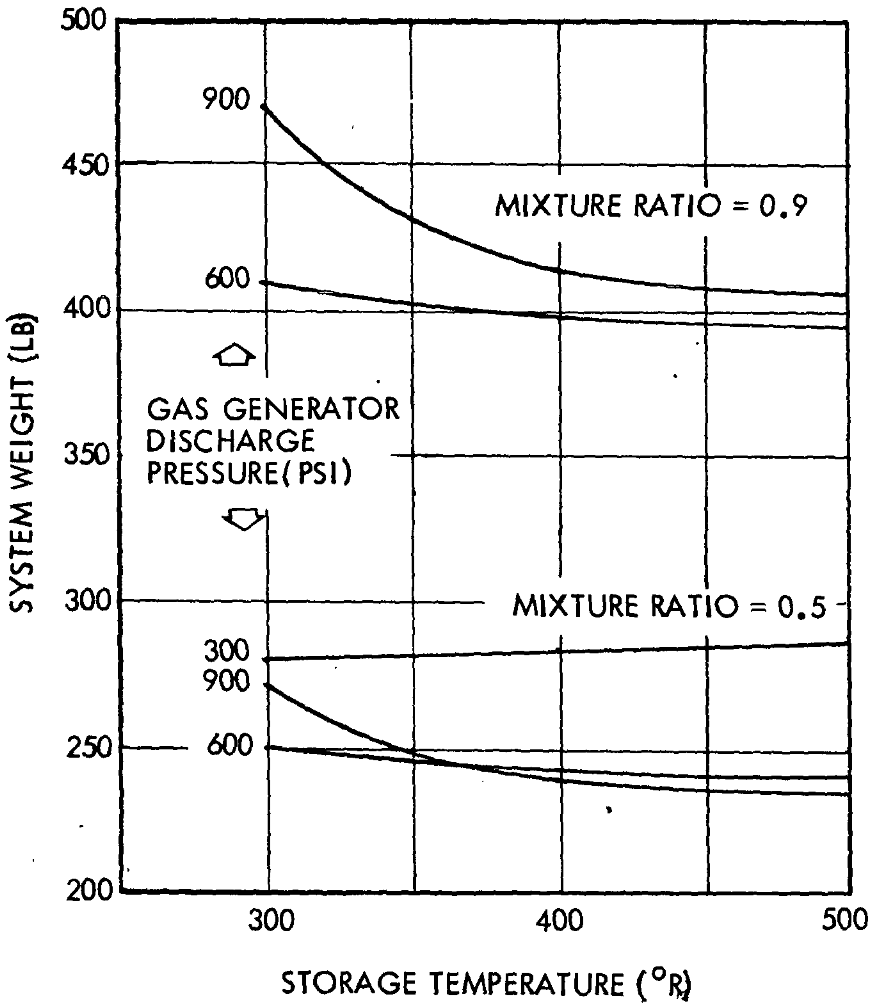

Fig. 9.4-13 APU System - Supercritical O_2 Storage System

WEIGHT VS. STORAGE TEMPERATURE

- 168-HOUR MISSION
- TWO 850-HP UNITS OPERATING
- OPTIMUM STORAGE PRESSURE
- INCLUDES WEIGHT OF STORAGE TANK, ACCUMULATOR, RESIDUALS, AND DELIVERED AND CONDITIONING O_2

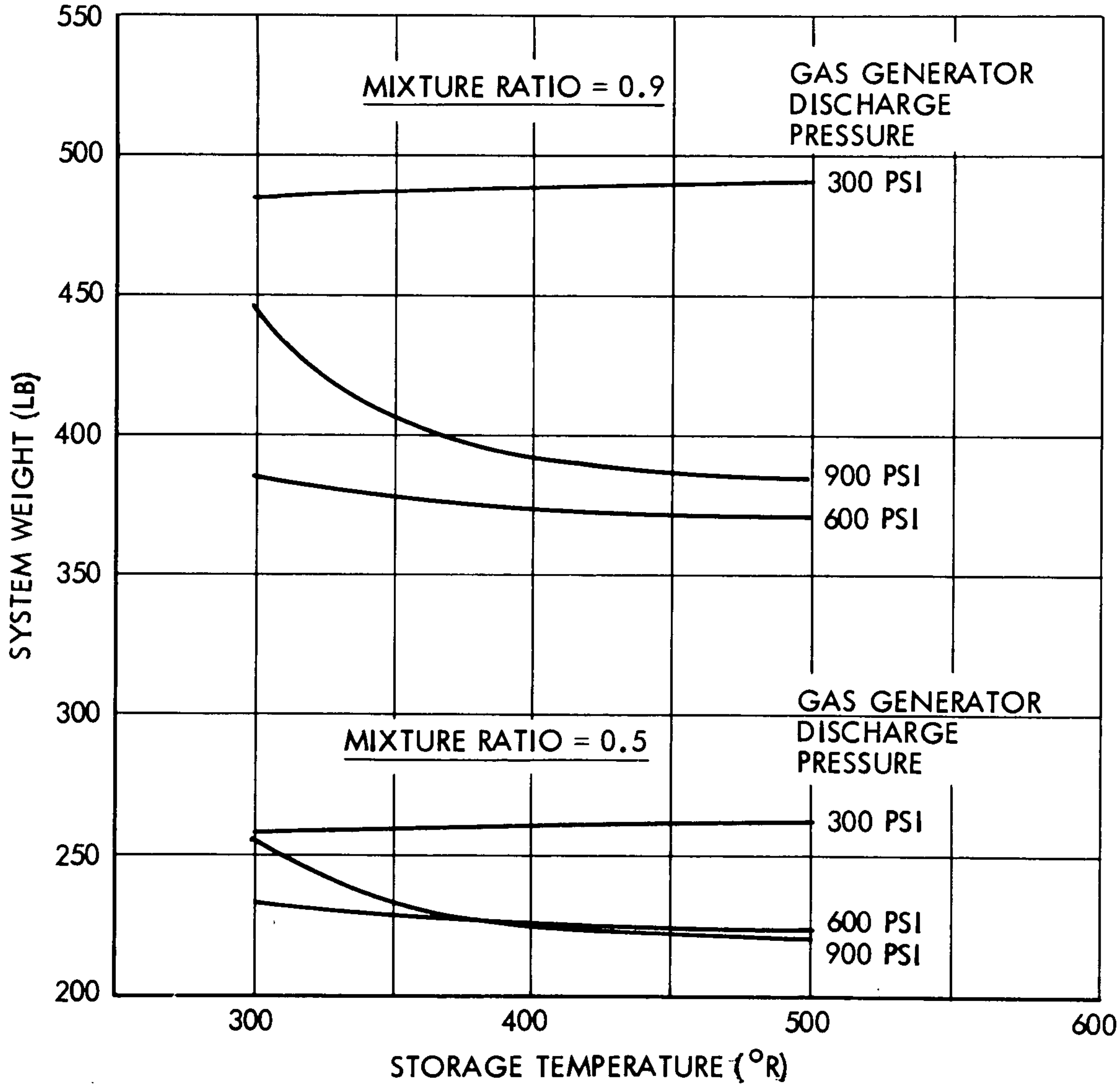

Fig. 9.4-14 APU System Supercritical O_2 Storage System

against 3-g acceleration during ascent and up to 2-g acceleration during reentry, or must allow gravity-draining during these periods of the duty cycles.

9.4.3 Auxiliary Power Unit Supply Tradeoff Studies

Auxiliary Power Unit Supply Tradeoff Studies compared subcritical and supercritical supply systems. The duty cycle employed in the evaluations is presented in Table 9.4-1. Propellant quantities were based on parametric propellant-flow data corresponding to 2260°R turbine-inlet temperature over a range of APU gas-generator discharge-pressures and mixture ratios. The matrix of APU conditions considered included the following:

Mixture Ratio	Gas-Generator Discharge-Pressure		
	900 psi	600 psi	300 psi
0.5	X	X	X
0.9	X	X	X

Total duty-cycle propellant flow was determined over this matrix of conditions for alternate cases of three 450-hp units in continuous operation and two 850-hp units in continuous operation. The inlet temperatures to the gas generators employed were:

- Mixture Ratio 0.5 - 1390°R
- Mixture Ratio 0.9 - 665°

9.4.3.1 <u>Subcritical Supply Tradeoff Studies</u>. Tradeoff studies for the subcritical supply subsystems were not significantly affected by storage conditions. Results of the optimization studies are presented in Table 9.4-2. The subcritical supply subsystems tend to optimize at the higher turbine-inlet pressures, as might be expected, since the subcritical storage with pump pressurization is not as sensitive to supply pressure as supercritical storage subsystems. As was found for the supercritical subsystems, the subcritical systems show a slight advantage in employing a O/F ratio of 0.5.

Table 9.4-1

APU DUTY CYCLE

PERIOD	MINUTES	MINUTES ON LOAD	LOAD, HP
PRELAUNCH C/O TO LIFTOFF	5	5	120
LIFTOFF TO 20,000 FEET	1	1	180
20,000 FEET TO SHUTDOWN	7	7	180
ORBIT C/O, START TO STOP	2	2	120
PREENTRY TO 270,000 FEET	42	42	60
270,000 FEET TO 20,000 FEET	48	40.5	30
–	–	7.5	850
20,000 FEET TO GO-AROUND	8	8	210
GO-AROUND TO TOUCHDOWN	6	6	210
TOUCHDOWN TO SHUTDOWN	2	2	850

Table 9.4-2

SUMMARY OF APU SUPERCRITICAL SUPPLY SYSTEM

	MIXTURE RATIO 0.5		MIXTURE RATIO 0.9	
	3–450 HP	2–850 HP	3–450 HP	2–850 HP
TANKAGE: H_2	110	123	106	123
O_2	12	12	16	16
H_2 TO APU	332	342	314	332
H_2 TO CONDITIONING AND PUMPING	51	53	53	56
H_2 RESIDUALS AND VENTED	41	43	41	44
O_2 TO APU	166	171	282	298
O_2 TO CONDITIONING AND PUMPING	51	53	53	56
O_2 RESIDUALS AND VENTED	3	4	3	5
COMPONENTS	669	669	650	650
ACCUMULATORS	23	23	42	42
He TANKS	4	4	4	4
TOTAL (LBS.)	1,462	1,497	1,565	1,626

9.4.3.2 Supercritical Supply Tradeoff Studies. Supercritical supply subsystem analyses and sensitivity studies, previously presented in subsection 9.4.2.2, were used in the selection of the optimum storage conditions. The selected optimized subsystems are presented in Table 9.4-3.

As seen from these data, there appears to be a slight weight advantage for the mixture ratio of 0.5. At a mixture ratio of 0.5, the gas-generator inlet pressure optimized near 300 psia, while at a mixture ratio of 0.9 psia, the gas-generator inlet pressure optimized at 600 psia.

9.4.3.3 Comparison of Subcritical and Supercritical Subsystems. There appears to be a significant weight advantage to the subcritical storage subsystems, which have the primary disadvantages of (1) requiring reactant acquisition devices and (2) having a somewhat severe pump duty-cycle requirement.

Table 9.4-3

SUMMARY OF AUXILIARY POWER UNIT
SUPERCRITICAL SUPPLY SYSTEM

		MIXTURE RATIO = 0.5		MIXTURE RATIO = 0.9	
		3 - 450 HP	2 - 850 HP	3 - 450 HP	2 - 850 HP
Tanks:	H_2	383 (300 psia/450/100°R)	414 (300 psia/450/100°R)	624 (600 psia/750/200°R)	660 (600 psia/750/200°R)
	O_2	26 (300 psia/750/300°R)	28 (300 psia/750/300°R)	48 (600 psia/750/200°R)	51 (600 psia/750/200°R)
Vacuum Jacket:	H_2	56	60	47	49
	O_2	3.5	3.7	4.5	4.75
Insulation:	H_2	32	34	28	29
	O_2	1	1	1.5	1.5
H_2 to APU		434	472	327	348
H_2 to Conditioning		27	29	58	61
H_2 Residuals		81	87	57	62
H_2 Vented		17	18	15	15
O_2 to APU		217	236	294	313
O_2 to Conditioning		27	29	58	61
O_2 Residuals		11	12	19	20
O_2 Vented		--	--	--	--
Components		784	784	765	765
Accumulators:	H_2	40	40	35	35
	O_2	5	5	9	9
TOTAL		2,145	2,253	2,390	2,484

9.5 FUEL CELL SUPPLY (FCS)

The Fuel Cell Supply (FCS) subsystem required a significantly less flowrate and heat addition rate than that required by the subsystems previously discussed. Accordingly, the FCS was less dependent upon duty cycle.

Consideration was given to the current fuel cell technology contracts:

- "Fuel Cell Technology Program", NAS 9-11034, Pratt & Whitney Aircraft
- "Fuel Cell Technology Program", NAS 9-11033, General Electric Company

The principal tradeoff in the Fuel Cell Supply was between the employment of subcritical and supercritical storage concepts.

9.5.1 Selection of Candidate Subsystems

The fuel cells considered in the study were defined by the respective manufacturers. Block diagram schematics for the Pratt and Whitney cell and the General Electric fuel cell systems are presented in Figs. 9.5-1 and 9.5-2, respectively. The flowrates, as shown, correspond to operation at a 10-kW steady-state load; this power level is representative of the average levels expected in active phases of the mission. Preliminary mass and thermal balances were performed on each system with the results presented in the figures. Reactant inlet temperatures and coolant temperatures were arbitrarily selected, and the heat balance calculations were made to indicate relative magnitudes of the heat loads and dissipations. The purge rates shown are overall system averages, not the rates at which the purge gas is flowing during the purging operation.

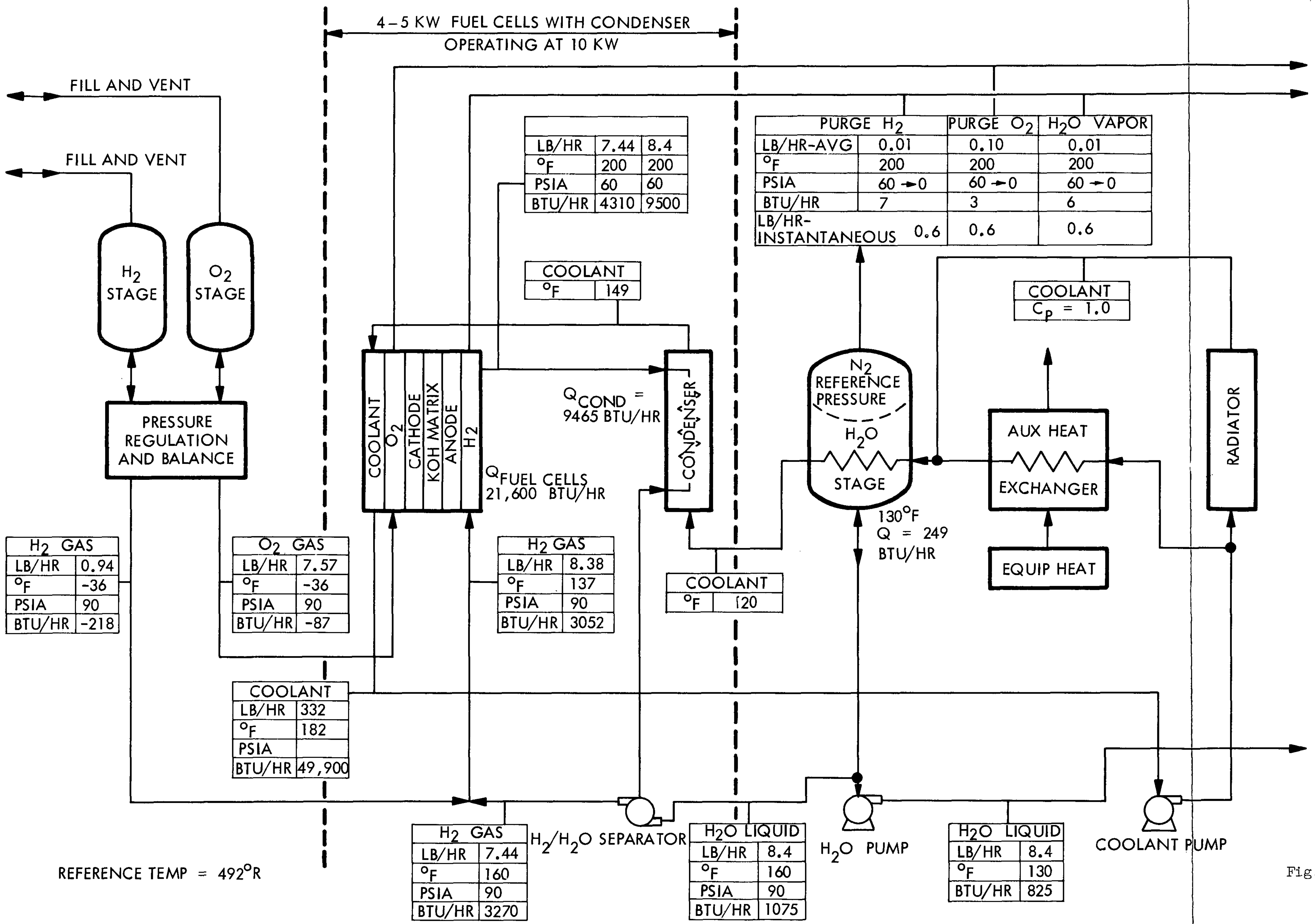

Fig. 9.5-1 Pratt & Whitney Fuel Cell Schematic

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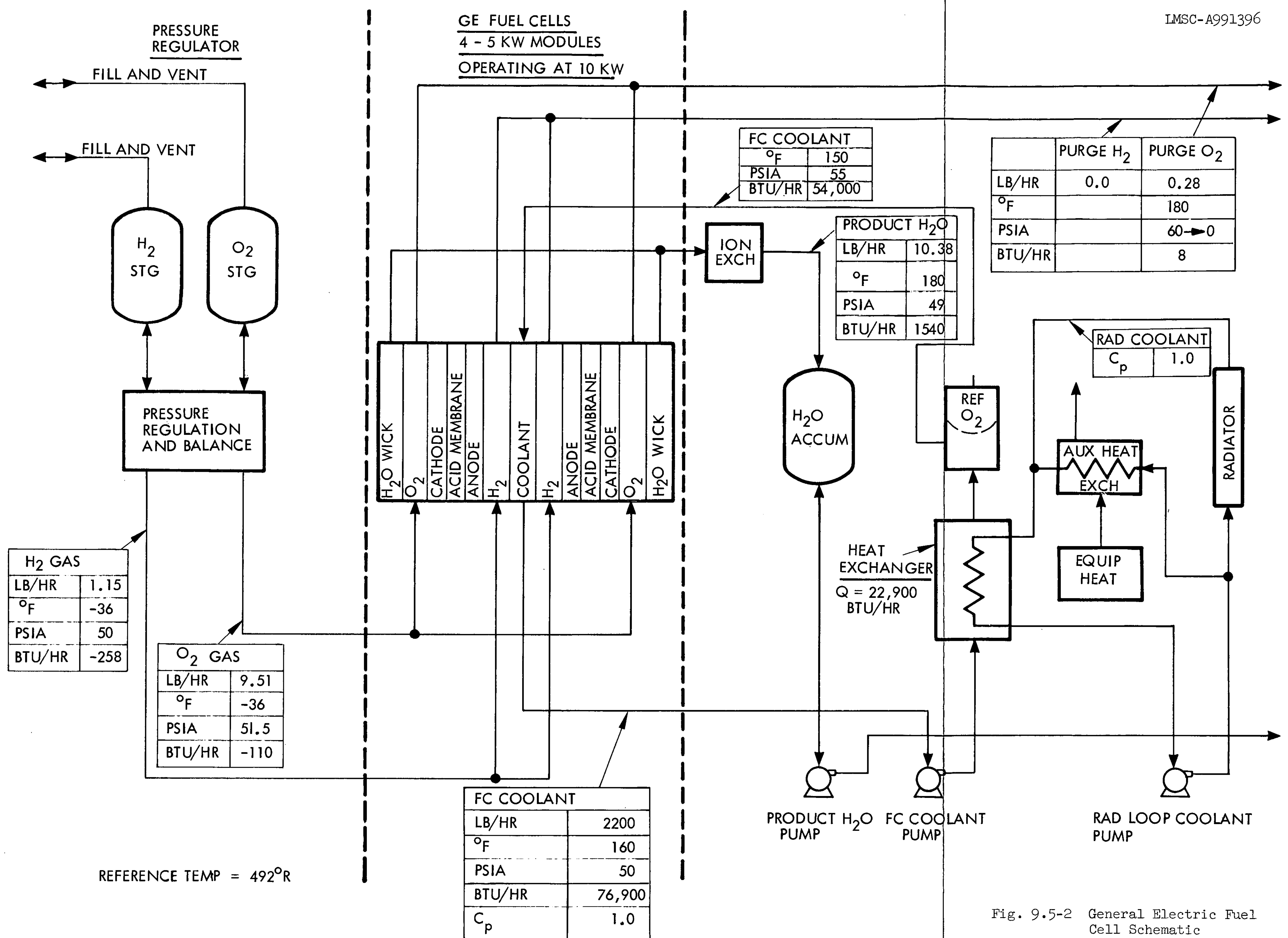

Fig. 9.5-2 General Electric Fuel Cell Schematic

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The P&W system is shown with a coolant used to condense the water and then absorb the heat dissipation within the fuel cell. Heat is rejected through a space radiator. Also, an auxiliary heat exchanger is shown without numerical values; this heat exchanger would be used during ascent and reentry, when the space radiator is inoperative. A water boiler could be used for this purpose. Another possibility would be to use the residual cryogens in the OMPS system as a heatsink (depending upon the coolant type and flowrates).

The GE fuel cell system is shown with two coolant loops, connected with an intermediate heat exchanger. This intermediate exchanger accepts the heat to be dissipated from the system and transfers it to a separate coolant loop that circulates through the space radiator. The space radiator itself is designed as part of the vehicle thermal control system, and the fuel cell load is only a portion of the heat to be rejected. Obviously, this dual-loop system also could be used with the P&W system. It does have the disadvantage, however, of resulting in lower radiator temperatures and, hence, larger radiators than would be required for the single-loop system.

Logically, the final conditioning of the reactants in the Fuel Cell Supply systems is through the use of the fuel cell waste heat. Conditioning is performed by the coolant loop. (The principal secondary coolant-loop candidate fluid is Freon 21.)

Considerations associated with the concepts are presented in Figs. 9.5-3, 9.5-4, and 9.5-5.

9.5.1.1 Schematics for Component Evaluations at AiResearch. Fuel Cell Supply schematics were prepared and submitted to AiResearch for the selection of components. These schematics, presented in Appendix E, were formulated to represent the possible component arrangements presented in Figs. 9.5-3, 9.5-4, and 9.5-5. Also, these schematics were used to perform the initial redundancy analyses using the SETA II Computer program. The identified redundancies (presented in Appendix E) established the least-reliable components in the subsystems.

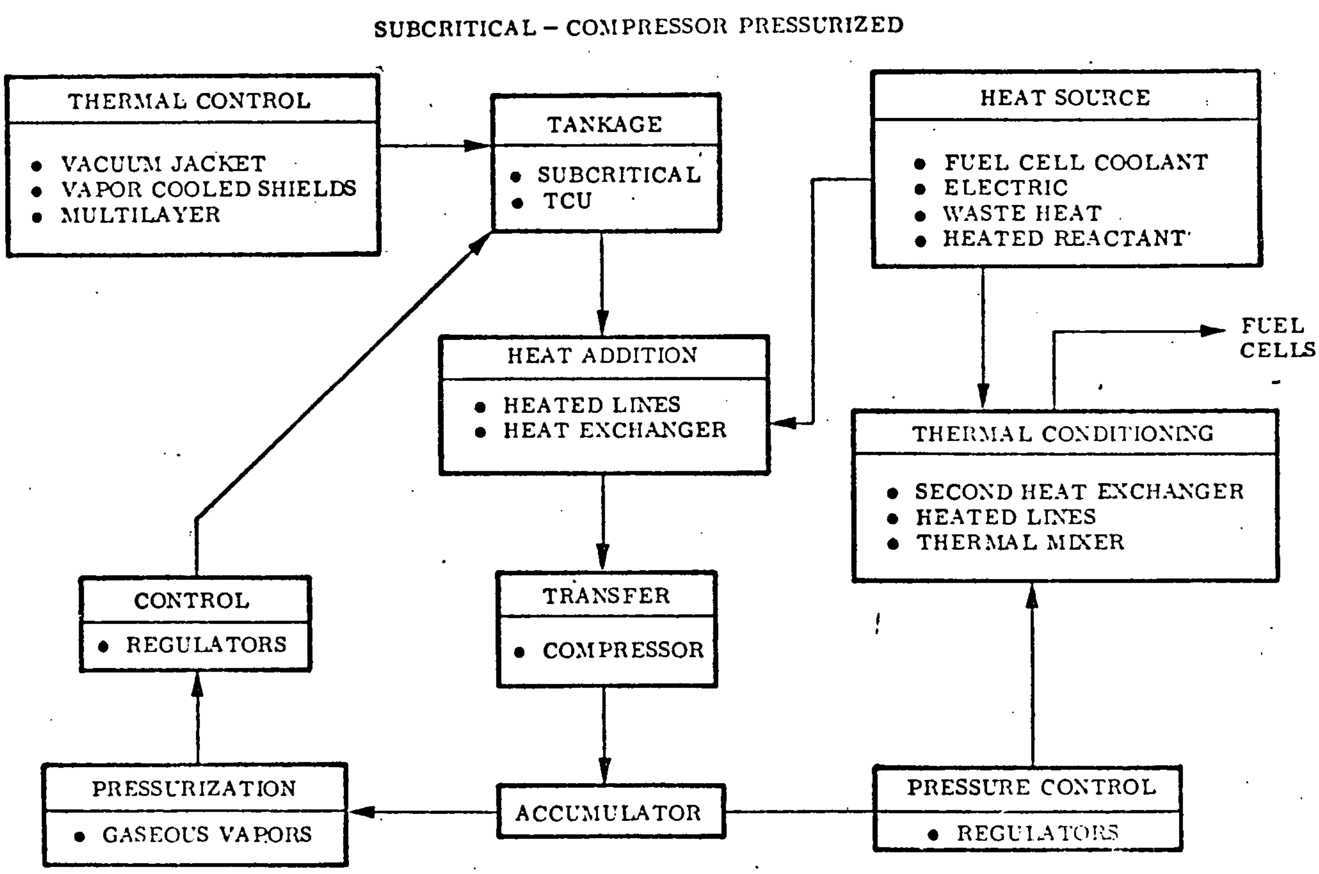

Fig. 9.5-3 Fuel Cell Supply System

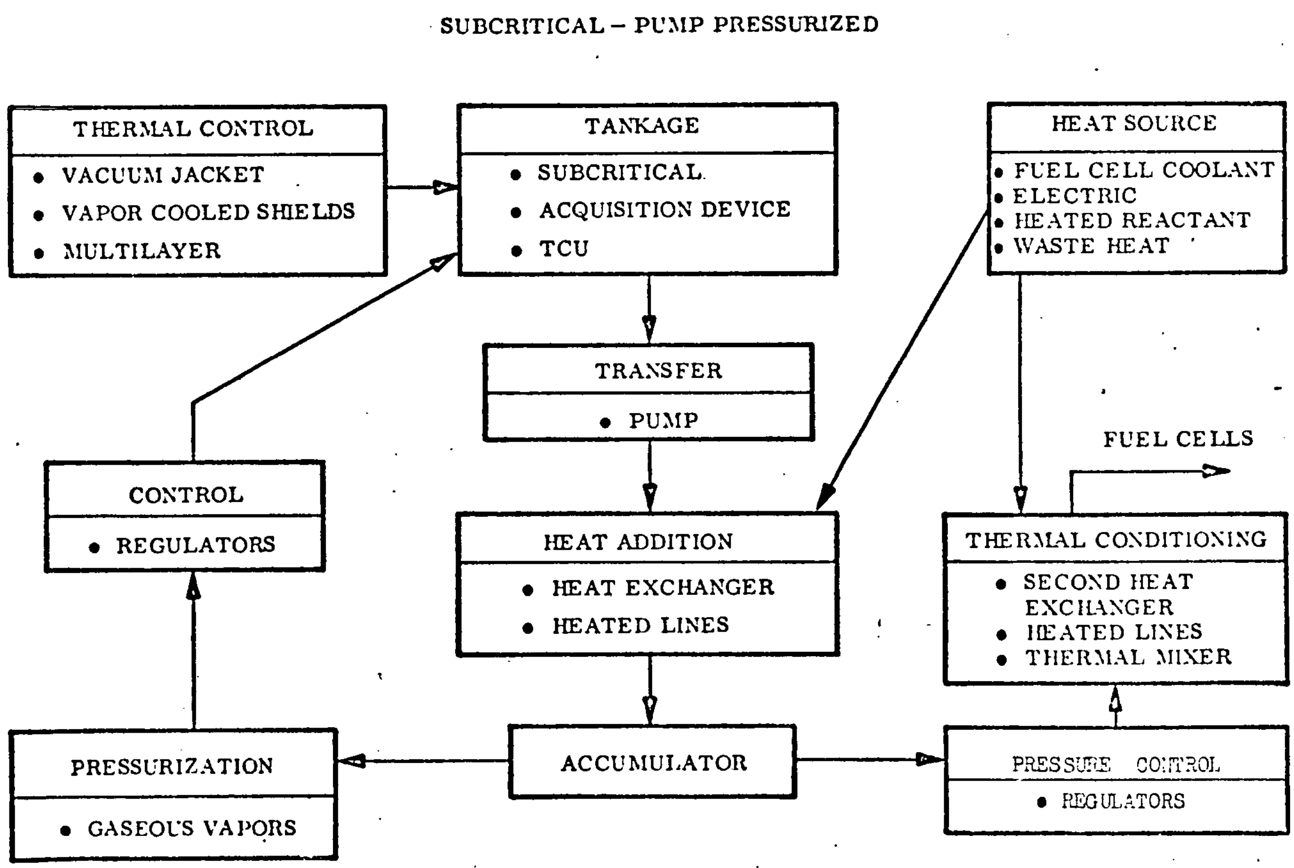

Fig. 9.5-4 Fuel Cell Supply System

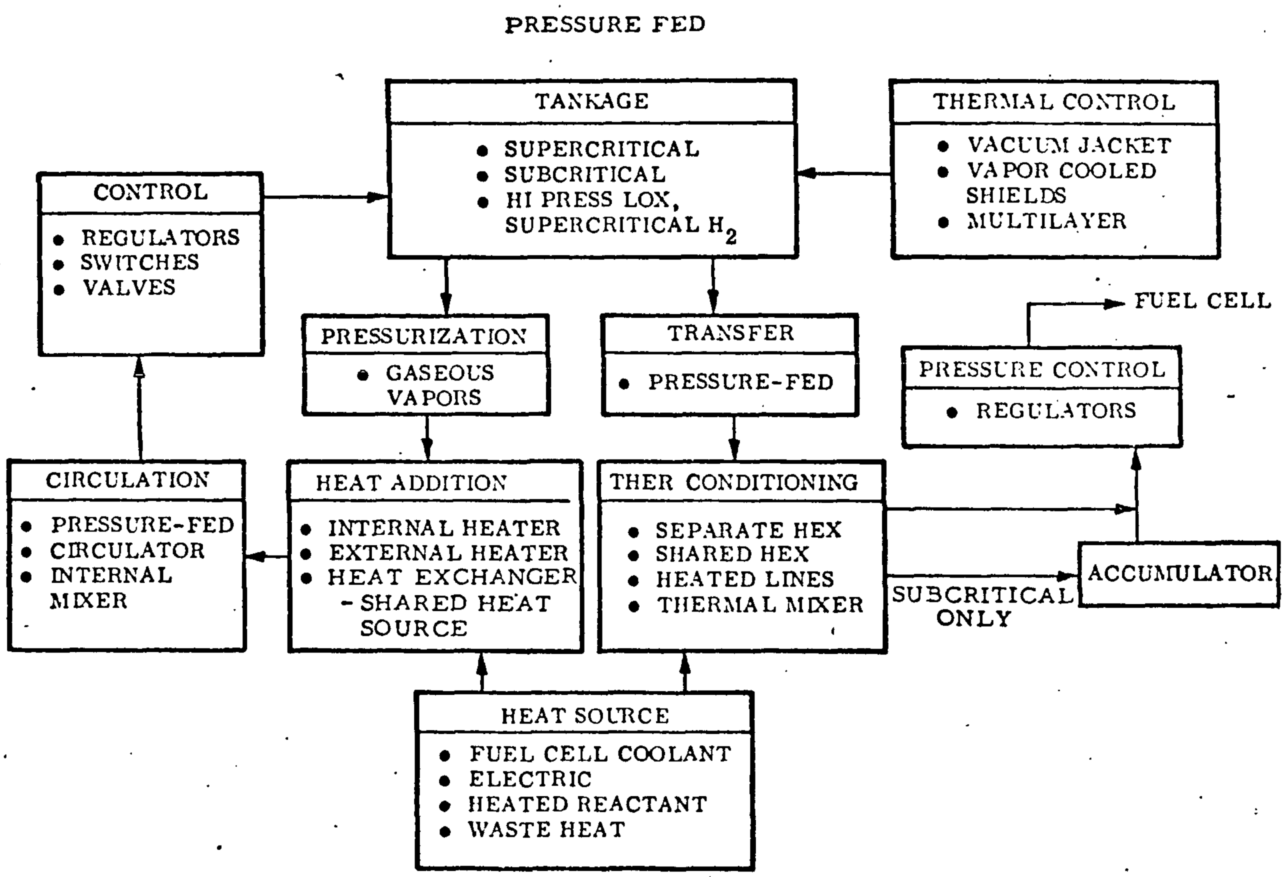

Fig. 9.5-5 Fuel Cell Supply System

9.5.1.2 Schematics for the Sensitivity and Tradeoff Studies. Schematics were prepared for use in the sensitivity and tradeoff studies. These schematics were put through several iterations to include developing safety criteria and instrumentation and control factors.

9.5.1.2.1 Supercritical Fuel Cell Supply Concept. The supercritical FCS schematic is presented in Fig. 9.5-6. Fuel cell heat is transferred to the secondary coolant loop, which is used to keep up the pressure in the supercritical tanks. Also, the coolant loop is used to adjust the temperature of the reactants prior to entering the fuel cells. The approach to satisfying the redundancy and safety criteria is to employ three separate supply feed systems from the same tanks.

9.5.1.2.2 Subcritical Fuel Cell Supply Concept. The schematic for the subcritical Fuel Cell Supply is presented in Fig. 9.5-7. Pressure in the supply tanks is maintained through the use of environmental heating; employment of a pump is not necessary because of the low flows under consideration. A possible alternate approach is to use helium pressurization, which necessitates the use of a very efficient reactant acquisition device to ensure liquid delivery.

Fuel cell waste heat is used to provide final conditioning of the reactants.

The redundancy and safety criteria are satisfied by employing three complete feed systems from the storage tanks.

9.5.2 Detailed Subsystem Analyses and Sensitivity Studies

The analyses and sensitivity studies presented in this section do not compare the approaches. Subsystem comparisons are provided in a subsequent section.

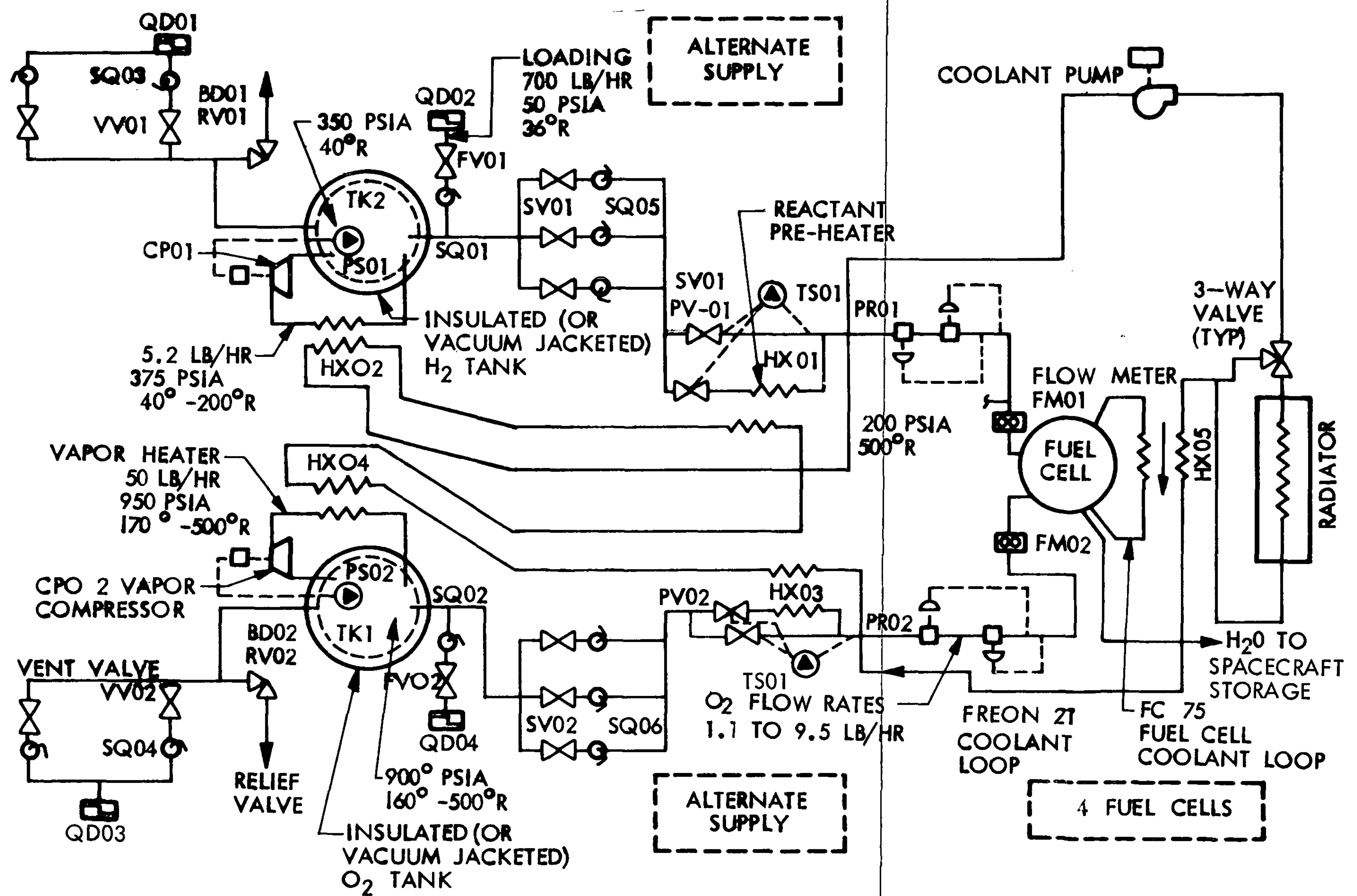

Fig. 9.5-6 Supercritical Fuel Cell Supply System

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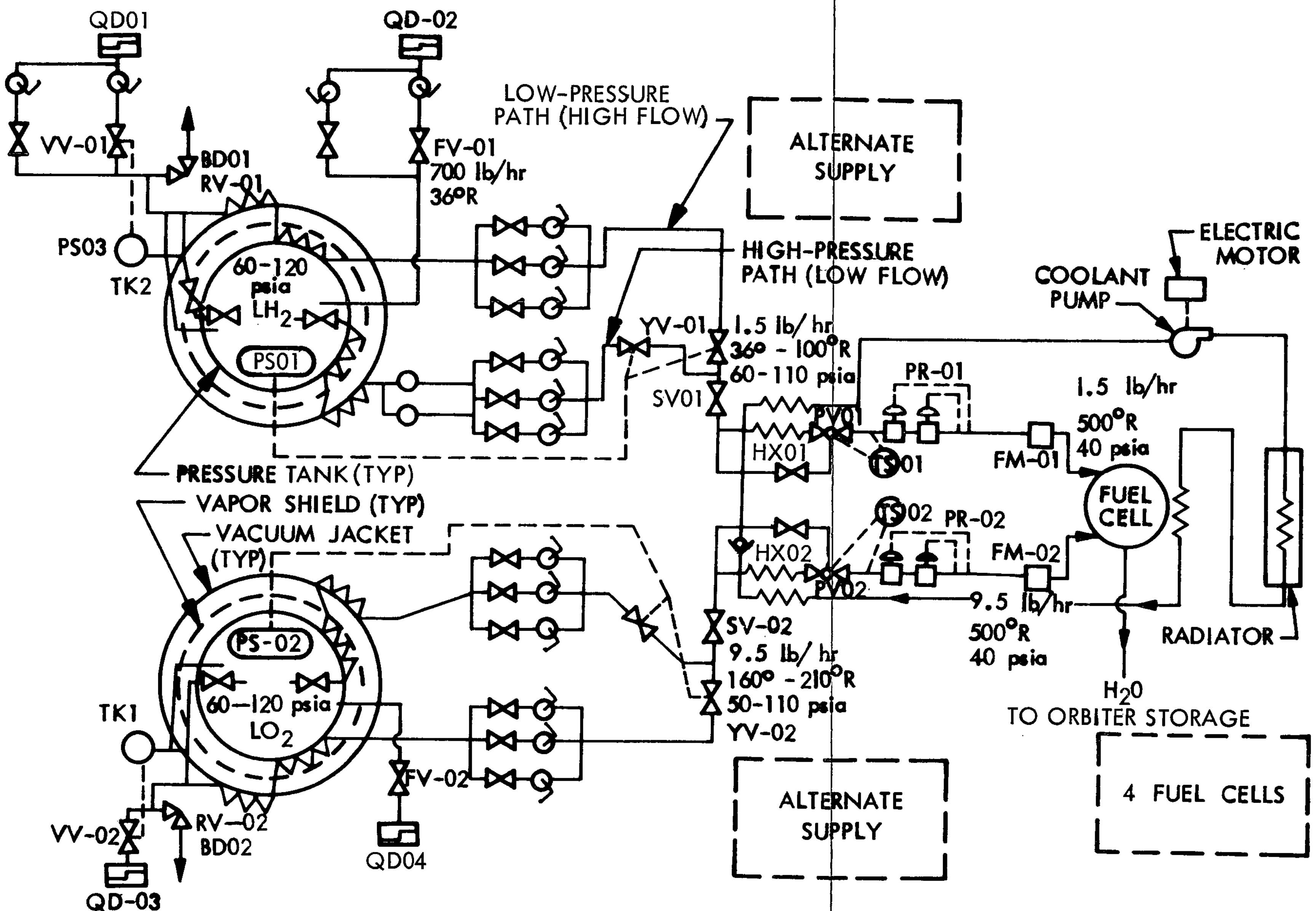

Fig. 9.5-7 Subcritical Fuel Cell Supply System

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The analyses for the Fuel Cell Supply system were based upon the maximum identified requirements of:

- Hydrogen - 175 lb
- Oxygen - 1,450 lb

9.5.2.1 Effects of FCS Pressure Upon Specific Reactant Consumption. Pratt and Whitney has provided data regarding the effects of fuel cell pressure on the specific reactant consumption, as presented in Table 9.5-1. These data were employed in the sensitivity and tradeoff studies in order to obtain the effects of the supply pressure.

Table 9.5-1

FUEL CELL REACTANT CONSUMPTION DATA
PRATT AND WHITNEY

	Minimum Supply Pressure (psia)			
	20	50	200	200
Operating Pressure - psia	15	45	45	60
Specific Weight - lb/kW at 7 kW	35	35	35	35
SRC - lb/kWh at 7 kW	0.86	0.82	0.83	0.82
Heat Rejection - Btu/kWh at 7 kW	2,400	2,100	2,200	2,100

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9.5.2.2 Supercritical Storage Analyses and Sensitivities. Analyses were performed to determine if the fuel cell waste heat output was sufficient under all conditions to provide the necessary reactant conditioning. The required conditioning for 1,450 lb of oxygen is presented in Fig. 9.5-8, and for 175 lb of hydrogen in Fig. 9.5-9. There is sufficient heat available from the fuel cells to provide the necessary reactant conditioning.

Supercritical storage conditions were examined to determine the optimum storage pressure. The weight index used in the evaluations consisted of the following:

- Tank weight
- Stored reactant weight
- Residual weight

Figure 9.5-10 presents analytical results of the supercritical storage of the fuel cell oxygen. These results indicate that the optimum storage pressure must be below 750 psia, which is below the minimum supercritical storage pressure for oxygen. As noted, there is a slight effect of the delivery pressure and the temperature of the reactants.

Similar results were obtained for the storage of the fuel cell hydrogen, as presented in Fig. 9.5-11. The optimum storage pressure was found to be below the minimum supercritical storage pressure for hydrogen, which is approximately 200 psia. Also, some effect is noted from the delivery temperature and the delivery pressures.

9.5.2.3 Effects of Helium Contamination on Purging. If helium is used for pressurization of liquid reactants for the fuel cells, helium will disolve in the reactant, be carried out of the tanks, and will act as a contaminant in the reactant. Such inert contamination increases the fuel cell purging requirements. The Pratt and Whitney fuel cell employs both hydrogen and oxygen purging; the General Electric fuel cell employs oxygen purging only. The purging requirements as a function of the purity of the reactants are provided in Fig. 9.5-12.

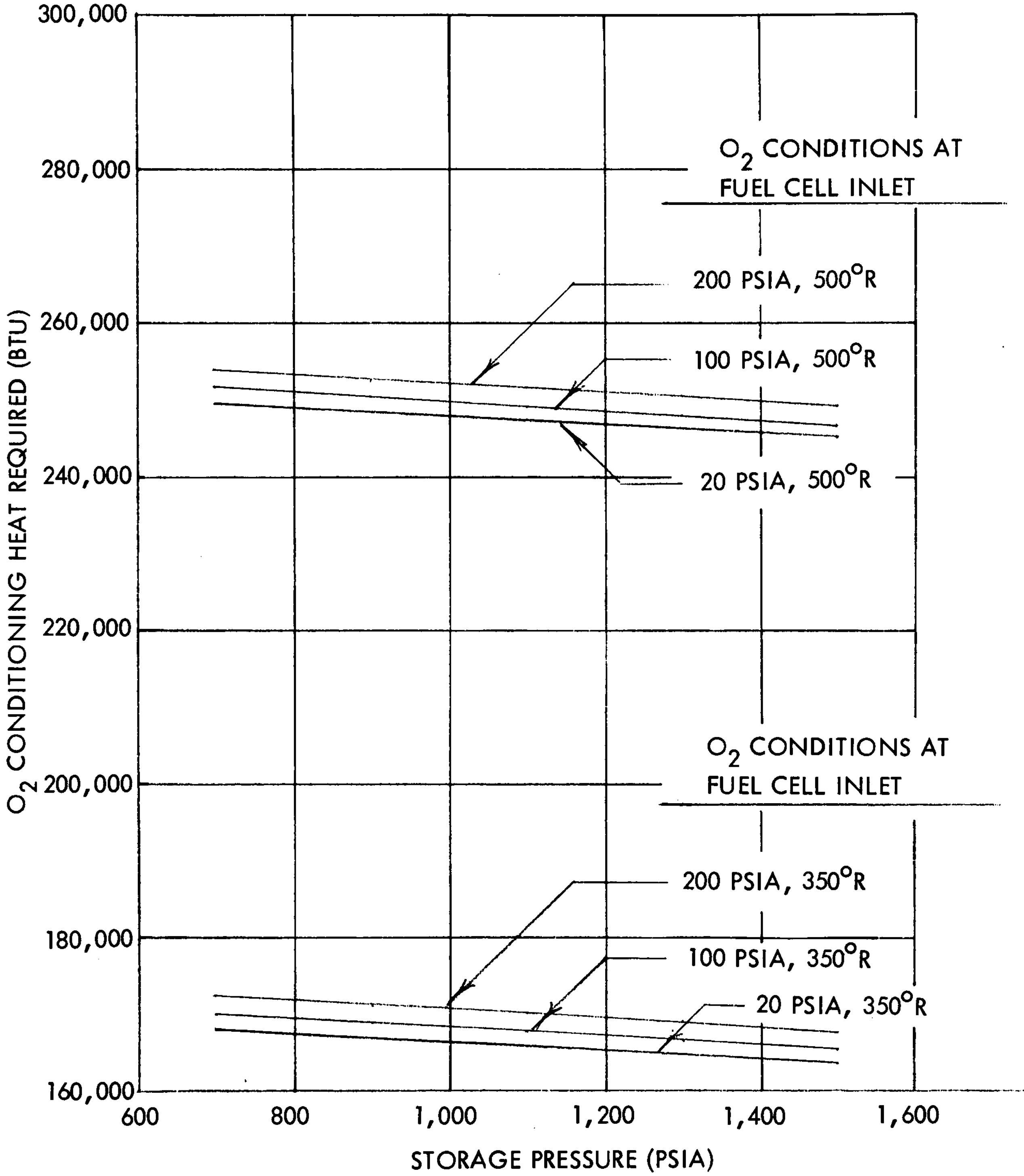

Fig. 9.5-8 O_2 Conditioning Heat
Supercritical Storage, Fuel Cell System

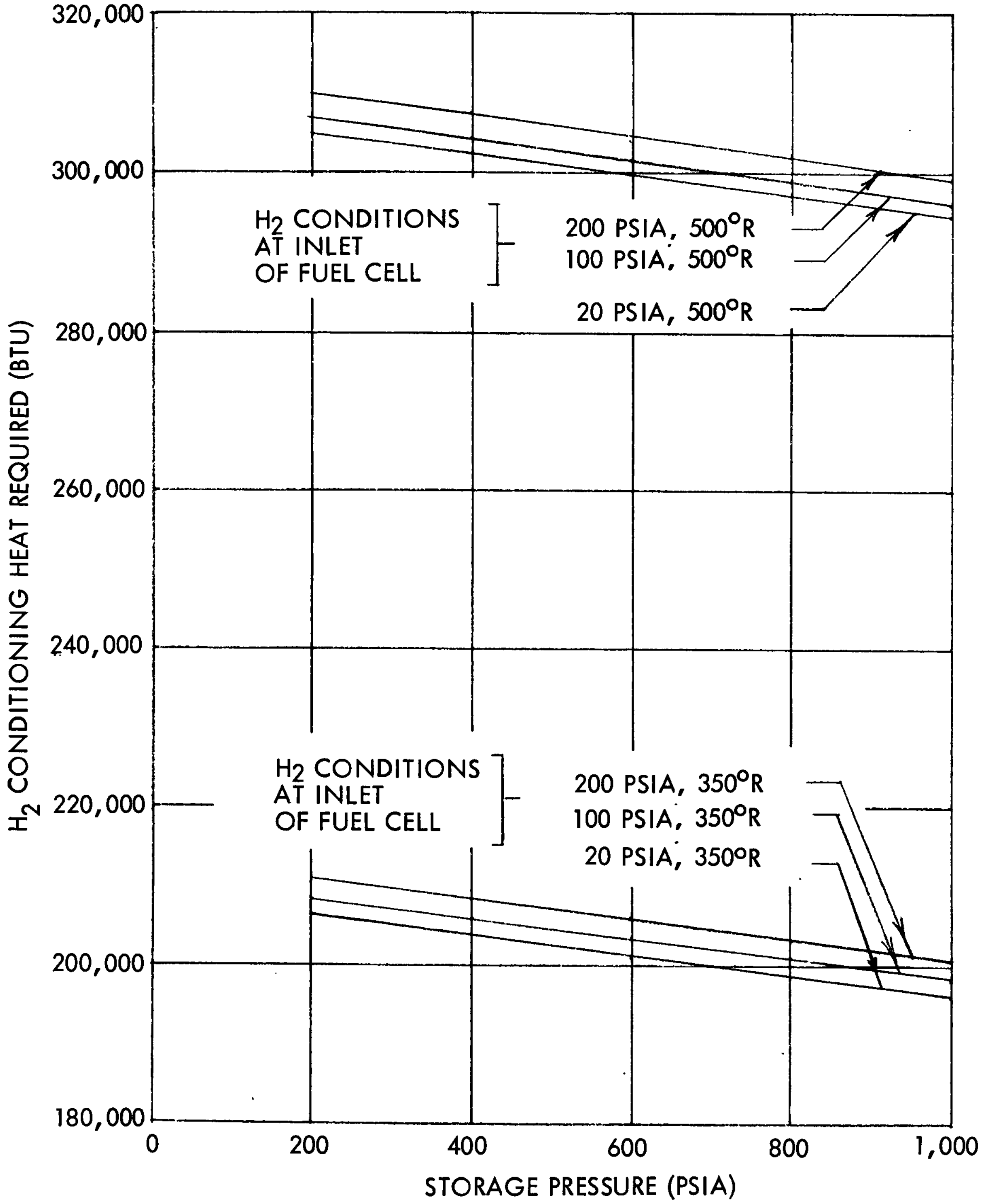

Fig. 9.5-9 H_2 Conditioning Heat
Supercritical Storage, Fuel Cell System

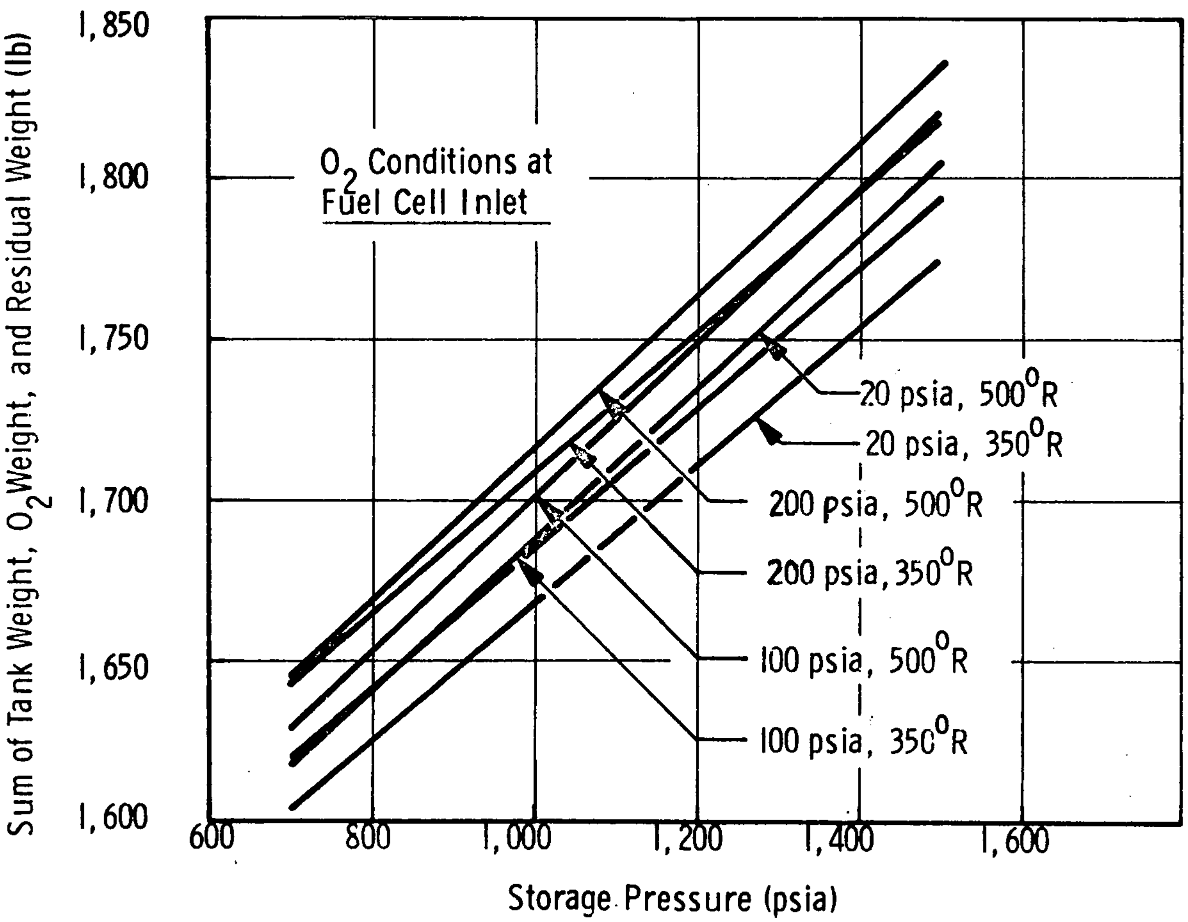

Fig. 9.5-10 O_2 System Weight — Supercritical Storage — Fuel Cell System

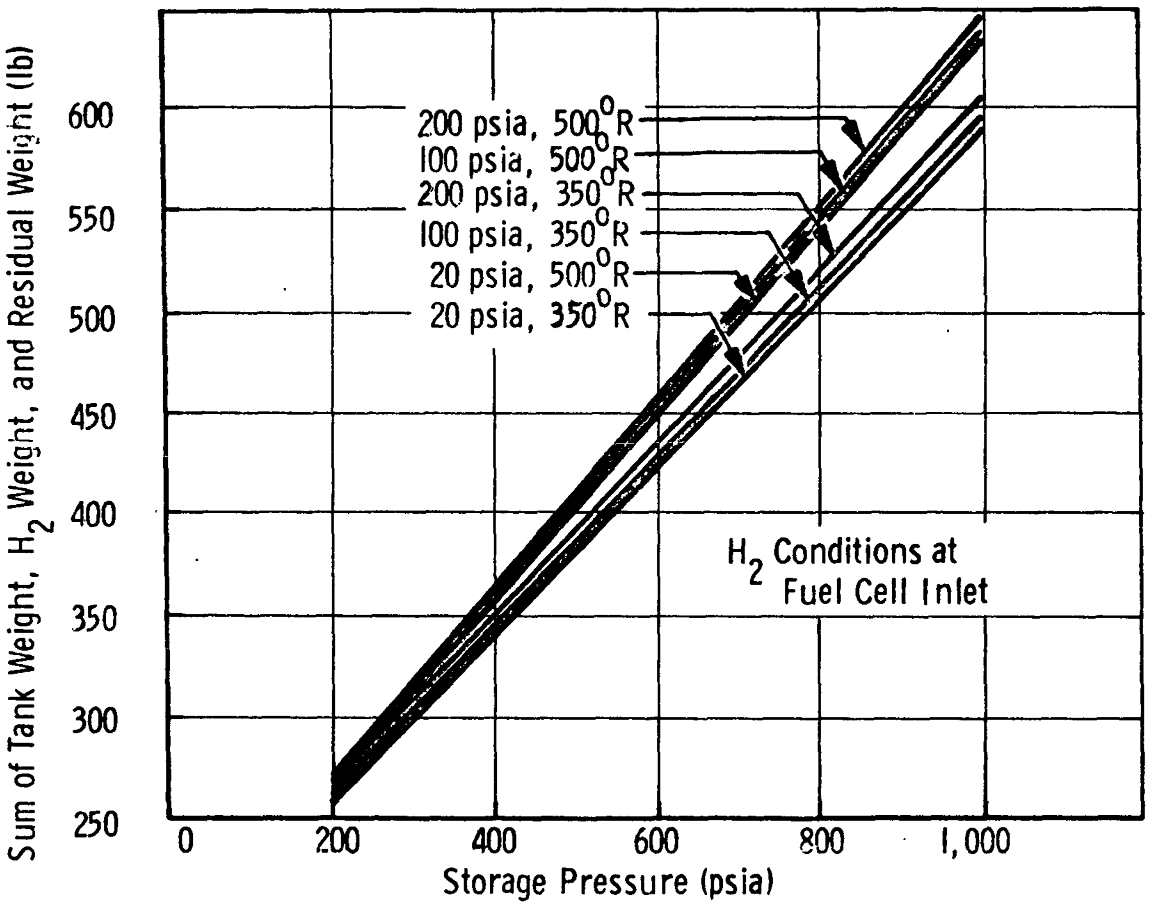

Fig. 9.5-11 H_2 System Weight — Supercritical Storage — Fuel Cell System

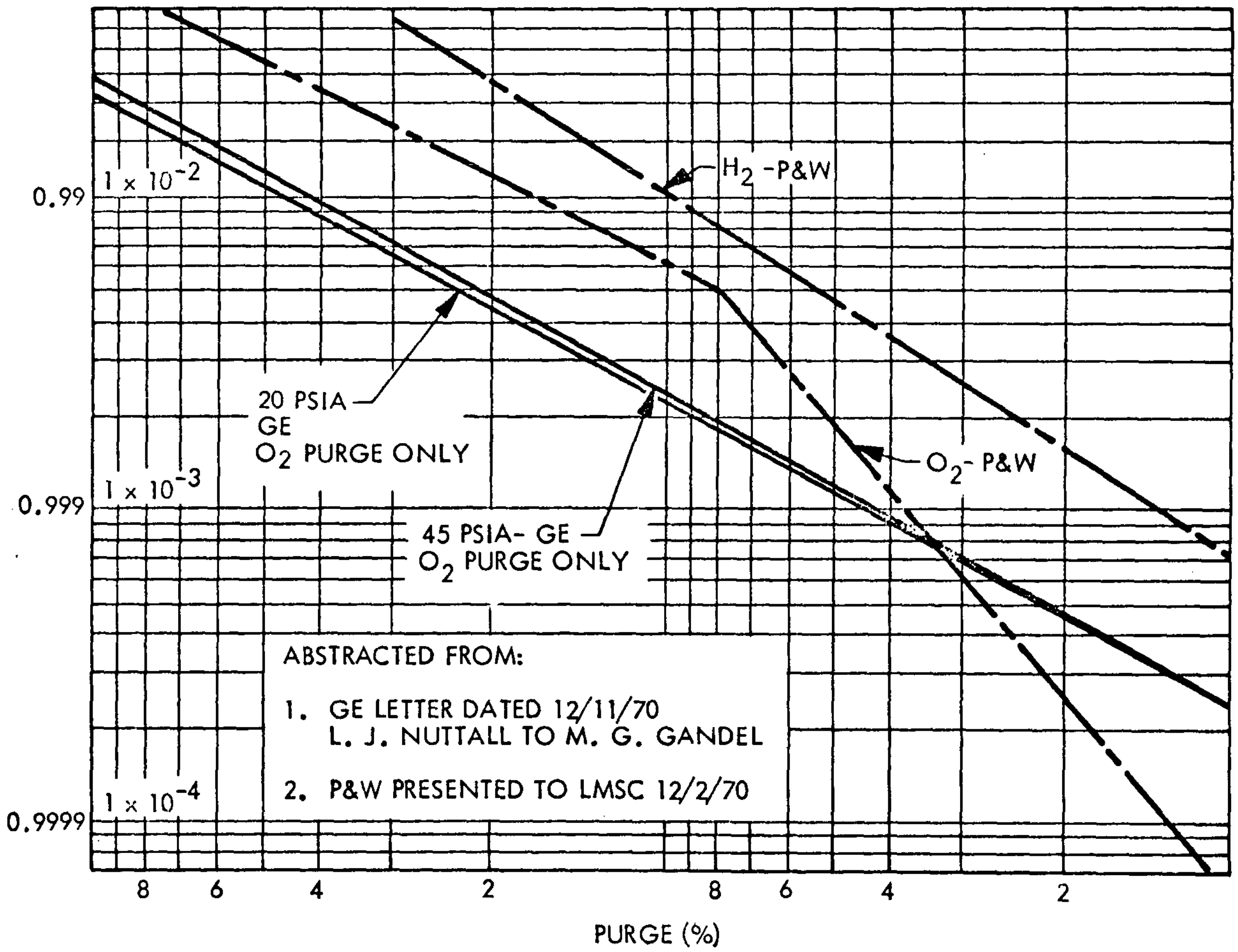

Fig. 9.5-12 Percent of Purge for Fuel Cells Vs Inert Concentration

The helium solubility in the cryogens is a function of the temperature of the cryogen and the total pressure on the system. Considerable data were available to LMSC on the solubility of helium in hydrogen; less data were available regarding the solubility of helium in oxygen.

Table 9.5-2 presents the results of analyses for helium contamination of hydrogen. It was assumed that the hydrogen would be near a temperature of $36.7^{\circ}R$ (corresponding to 18-psia vapor pressure). As noted in the table, the percentage of hydrogen required for purging is relatively small.

Oxygen purging data are presented in Table 9.5-3. Because of the limited data available, the analyses were performed for a total pressure of 250 psia and for several temperatures. As may be seen, the purge requirements are negligible.

Another factor that enters into consideration is the number of valve cycles associated with the purging. These analyses were not performed in this evaluation.

5.5.3 Fuel Cell Supply Tradeoff Studies

The Fuel Cell Supply system approaches that were compared are presented in Figs. 9.5-6 and 9.5-7. These comparisons were based upon the Pratt and Whitney fuel cell data regarding supply pressures and specific reactant consumption. Component data were obtained from the AiResearch inputs and from parametric data presented in the Task Reports.

A comparison of supercritical and subcritical storage is presented in Table 9.5-4. The comparison indicates that there is an insignificant difference between the supercritical and subcritical storage of the fuel cell reactants. It is believed that this can be contributed principally to the very high oxidizer-to-fuel ratio employed in fuel cells, which makes the storage of hydrogen less significant than in many other types of subsystems. Even if the component weights were the same, the overall differences would be less than 100 lb.

Another observation from these data is that the very low supply pressures did not result in weight savings. The additional reactant required, coupled with minimum gage and minimum component weight considerations, resulted in overall weight increases.

Table 9.5-2

FUEL CELL – HYDROGEN PURGING REQUIRED BY HELIUM CONTAMINATION

Initial Tank Pressure psia	Dissolved Helium Wt. %	Purity	Pratt & Whitney Fuel Cell Purge H_2 Consumption % of Flow
20	0.556	99.444	0.62
35	0.675	99.325	0.74
50	0.814	99.186	0.88
75	1.211	98.789	1.20
100	1.668	98.332	1.66
125	2.085	97.915	1.90
150	2.58	97.42	2.30
175	3.058	96.942	2.60
200	3.316	96.684	2.80
Initial Conditions: Temp – 36.7°R Press.– 18 psia			

Table 9.5-3

FUEL CELL – OXYGEN PURGING REQUIRED BY HELIUM CONTAMINATION

Initial Tank Pressure psia	Temp. °R	Dissolved Helium Wt. %	Purity	Purge Consumption % of Flow	
				P&W Fuel Cell	G. E. Fuel Cell
250	139	0.005	99.995	0.1%	Neg.
	168	0.0175	99.9825	0.18	0.075
	203	0.0336	99.9664	0.23	0.15

Table 9.5-4

COMPARISON OF FUEL CELL SUPPLY – SYSTEM APPROACHES

ITEM	MIN. SUPPLY PRESSURE (PSIA)	SUPERCRITICAL 20	SUPERCRITICAL 100	SUPERCRITICAL 200	SUBCRITICAL 20	SUBCRITICAL >60
TANKAGE:	O_2	180	169	171	50	60
	H_2	115	113	114	79	90
COMPONENTS		199	199	199	311	311
REACTANTS:	O_2	1520	1450	1450	1520	1450
	H_2	184	175	175	184	175
RESIDUALS:	O_2	3.52	18.85	39.1	19	36
	H_2	0.43	2.2	4.4	2	4
TOTAL		2202	2127	2153	2165	2126

9.6 LIFE SUPPORT SUPPLY (LSS)

The Life Support Supply subsystem flowrates and conditioning requirements are extremely low, and the system does not represent large weight effects as the other cryogenic subsystems. It was considered to be beyond the scope of this study to determine the requirements of the system with regard to division of storage, repressurization, and similar possibilities. Several related studies were examined including:

- Space Shuttle Environmental Control/Life Support System Study, NAS 1-10359, February 1971, Hamilton Standard.
- Study of Space Shuttle Environmental Control and Life Support Problems, NAS 1-10478, July 1971, Lockheed Missiles & Space Company.

9.6.1 Selection of Candidate Subsystems

Considerations associated with the concepts are presented in Fig. 9.6-1.

9.6.1.1 Schematics for Component Evaluations at AiResearch. Life Support Supply schematics were prepared and submitted to AiResearch for the selection of components. These schematics, presented in Appendix E, were formulated to represent the possible component arrangements. Also, these schematics were used to perform the initial redundancy analyses using the SETA II Computer program. The identified redundancies (presented in Appendix E) established the least-reliable components in the subsystems.

9.6.1.2 Schematics for the Tradeoff Studies. The schematics were examined to include the necessary redundancy and safety criteria and the instrumentation and control. Revised schematics are presented in Figs. 9.6-2 and 9.6-3.

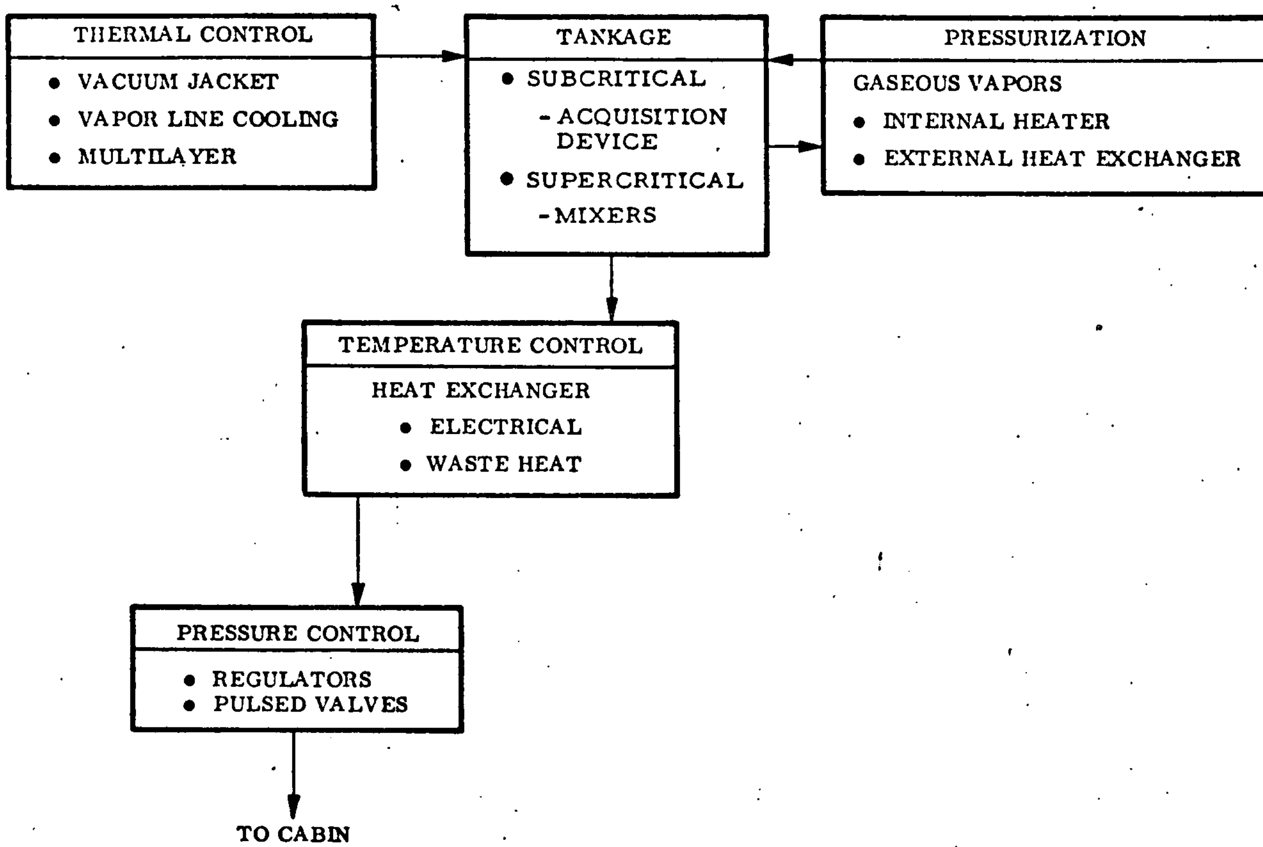

Fig. 9.6-1 EC/LSS Gas Supply and Pressure Control

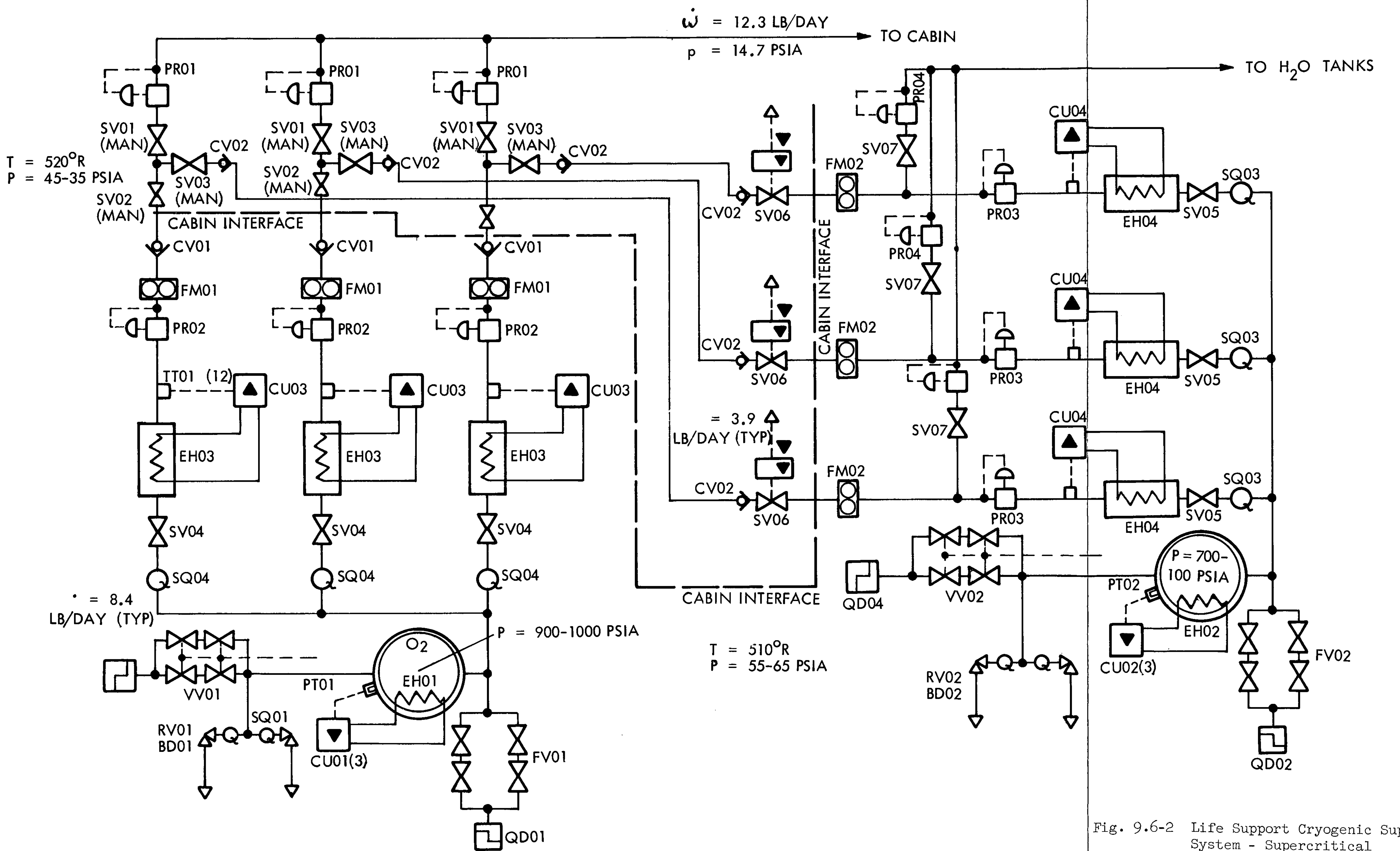

Fig. 9.6-2 Life Support Cryogenic Supply System - Supercritical

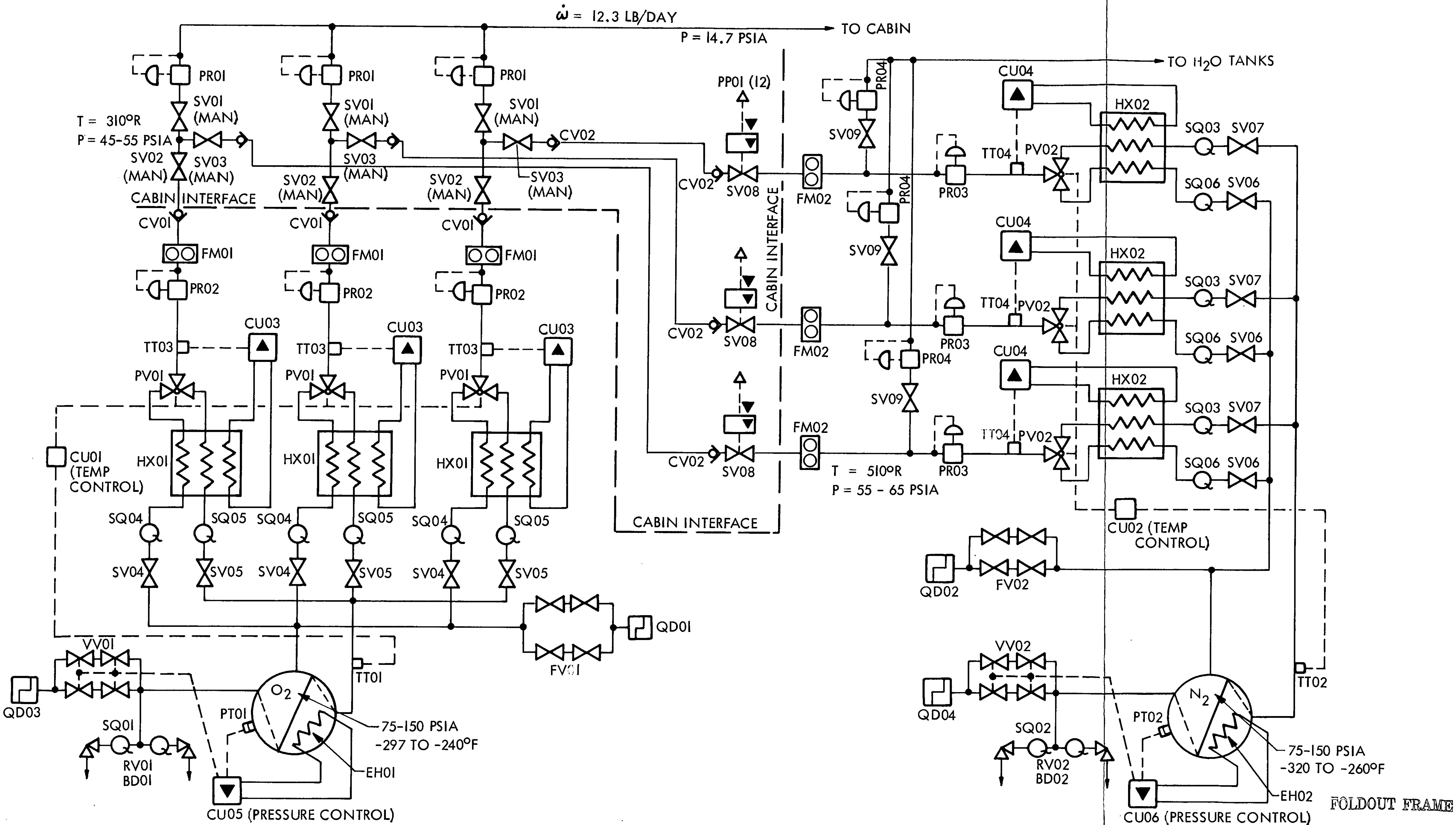

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Fig. 9.6-3 Life Support Cryogenic Supply System – Subcritical

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9.6.2 Life Support Supply Tradeoff Studies

Studies were not performed to compare high-pressure gas storage with cryogenic storage. However, studies were conducted in "Space Shuttle Environmental Control/Life Support System Study," NAS 1-10359, which compared high-pressure storage with cryogenic storage, and various high-pressure storage methods. Results indicated that cryogenic storage was more effective. For high-pressure storage, the most effective method was found to be cryogenically formed stainless steel (Ardeform), reinforced with fiberglass laminate. This study projected a weight of 0.8 lb of tank per lb of gas stored at 3,000 psia.

Weight statements have been prepared for the schematics shown in Figs. 9.6-2 and 9.6-3, and are presented in Tables 9.6-1 and 9.6-2. As may be seen from these tables, subcritical storage would offer no advantages over supercritical storage. This completes a trend, which started with the ACPS and progressed down through the APU, Fuel Cell, and EC/LSS, indicating that as propellant and reactant volumes decrease, the advantage of subcritical storage decreases.

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Table 9.6-1

LIFE SUPPORT SUBSYSTEM WEIGHT – SUPERCRITICAL SYSTEM

Subsystem	Weight (lb)
O_2 Supply	
• Components	61.6
• Lines	7.3
• Storage Tank	8.4
– Vacuum Shell plus Insulation	3.6
N_2 Supply	
• Components	85.5
• Lines	7.3
• Storage Tank	10.8
– Vacuum Shell plus Insulation	4.3
Conditioning	
• Tank Weight Penalty (Fuel Cell System)	1.8
Total Dry Weight	190.6 lb
Fluids	
• Usable O_2	50.0
• Usable N_2	65.0
• Conditioning Cryogens	6.0
• Residuals	1.2
Total Fluids	122.2 lb
Total Subsystem Weight	312.8 lb

Table 9.6-2

LIFE SUPPORT SUBSYSTEM WEIGHT – SUBCRITICAL SYSTEM

Subsystem	Weight (lb)
O_2 Supply	
• Components	81.2
• Lines	7.3
• Storage Tank	3.4
– Vacuum Shell plus Insulation	3.6
N_2 Supply	
• Components	110.4
• Lines	7.3
• Storage Tank	4.8
– Vacuum Shell plus Insulation	5.2
Conditioning	
• Tank Weight Penalty (Fuel Cell System)	1.8
Total Dry Weight	225.0 lb
Fluids	
• Usable O_2	50.0
• Usable N_2	65.0
• Conditioning Cryogens	6.0
• Residuals	1.2
Total Fluids	122.2 lb
Total Subsystem Weight	347.2 lb

9.7 PURGING, INERTING, AND PNEUMATIC SUPPLY (PIPS)

The Purging, Inerting, and Pneumatic Supply (PIPS) subsystems can result in a significant subsystem weight. The weight penalty is very dependent upon the safety criteria, which is adopted for the Space Shuttle. Some of the major considerations are:

- Do hydrogen tanks have to be inerted prior to reentry?
- Is the dilution of hydrogen leakage needed during reentry?
- To what extent is insulation purging used as opposed to vacuum jacketing?

Data presented in this report do not answer these questions but present the associated requirements and system weights related to the alternatives.

9.7.1 Selection of Candidate Subsystems

The candidate Purging, Inerting, and Pneumatic Supply subsystem alternatives are principally the result of combining approaches to the storage of helium and nitrogen. Considerations associated with the concepts are presented in Figs. 9.7-1 and 9.7-2.

9.7.1.1 Schematics for Component Evaluations at AiResearch. Purging, Inerting, and Pneumatic Supply schematics (Appendix E) were prepared and submitted to AiResearch for the selection of components. The schematics were formulated to represent the possible component arrangements presented in Figs. 9.7-1 and 9.7-2. Also, these schematics were used to perform the initial redundancy analyses using the SETA II Computer program. The identified redundancies, presented in Appendix E, established the least-reliable components in the subsystems.

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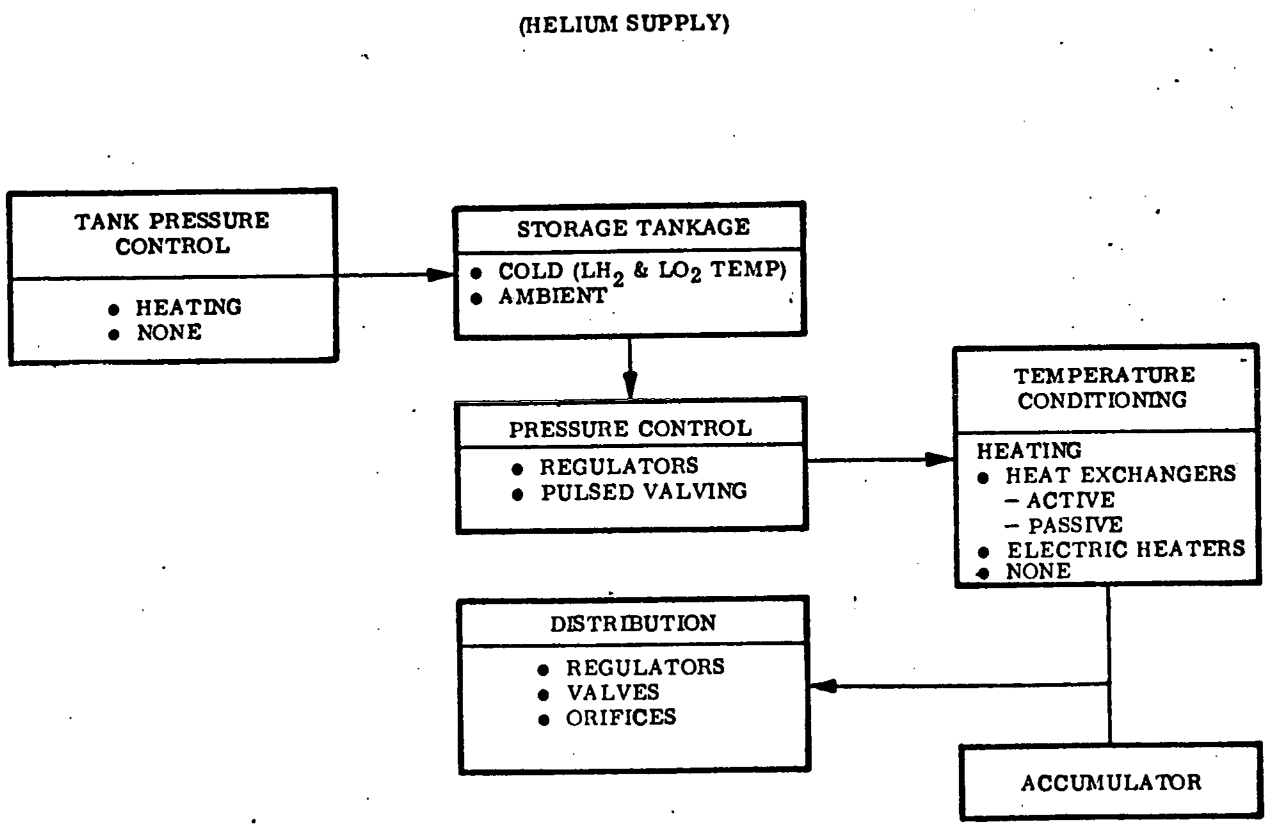


Fig. 9.7-1 Purging, Inerting, and Pneumatic Supply System

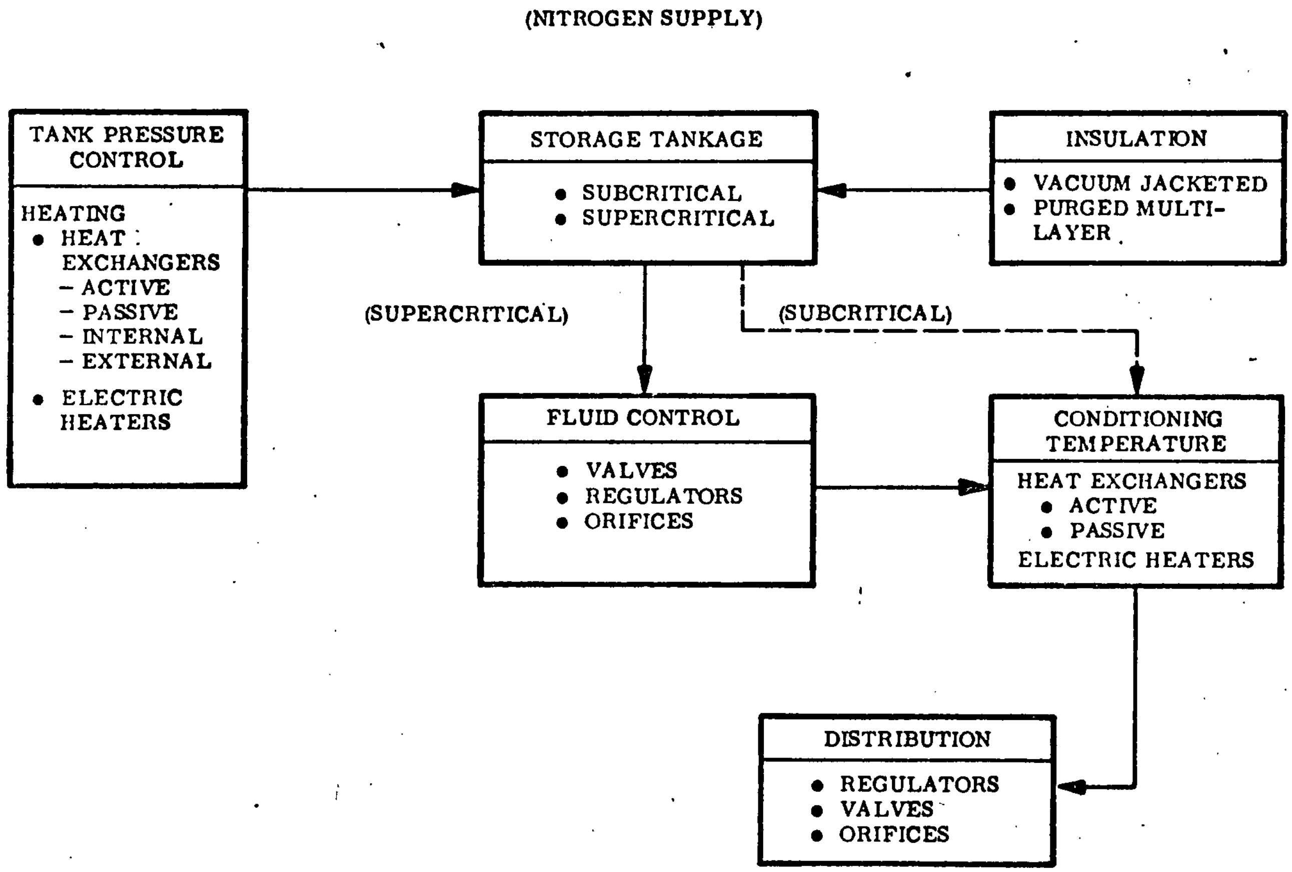


Fig. 9.7-2 Purging, Inerting, and Pneumatic Supply System

9.7.1.2 Schematics for Analyses and Tradeoff Studies. Detailed schematics were prepared for the PIPS analyses and tradeoff studies. The schematics include the necessary safety and redundancy. The concepts are discussed in the following paragraphs:

9.7.1.2.1 Storage of Gaseous Helium at Liquid-Hydrogen Temperatures. Helium storage at liquid-hydrogen temperatures allows storage at high pressure with minimum tank volume and subsequent weight. The storage may be by location of the storage tank in the liquid hydrogen, or possibly, preferably under the insulation system on the exterior of the liquid-hydrogen tank.

Heating of the helium will require a heat exchanger employing a GO_2/GH_2 gas generator. This is necessary for the high flowrate requirements. This is presented in Fig. 9.7-3.

9.7.1.2.2 Storage of Helium at Ambient Conditions. Helium is stored in high-pressure tanks under ambient conditions. Heaters may still be required to maintain temperatures under high rates of tank blowdown. This is presented in Fig. 9.7-4.

9.7.1.2.3 Subcritical Storage of Liquid Nitrogen. The subcritical storage of liquid nitrogen is a volumetric tank-weight efficient method. A high capacity gas generator-heated exchanger is required for heating for the high flowrates. This is presented in Fig. 9.7-5.

9.7.1.2.4 Supercritical Storage of Nitrogen. The supercritical storage of nitrogen is the best alternative to subcritical storage. The schematic is presented in Fig. 9.7-6.

9.7.1.2.5 Ground Purging. The ground purging subsystem does not require storage of purge gas. This subsystem consists only of a distribution system operating from ground supply, as shown in Fig. 9.7-7.

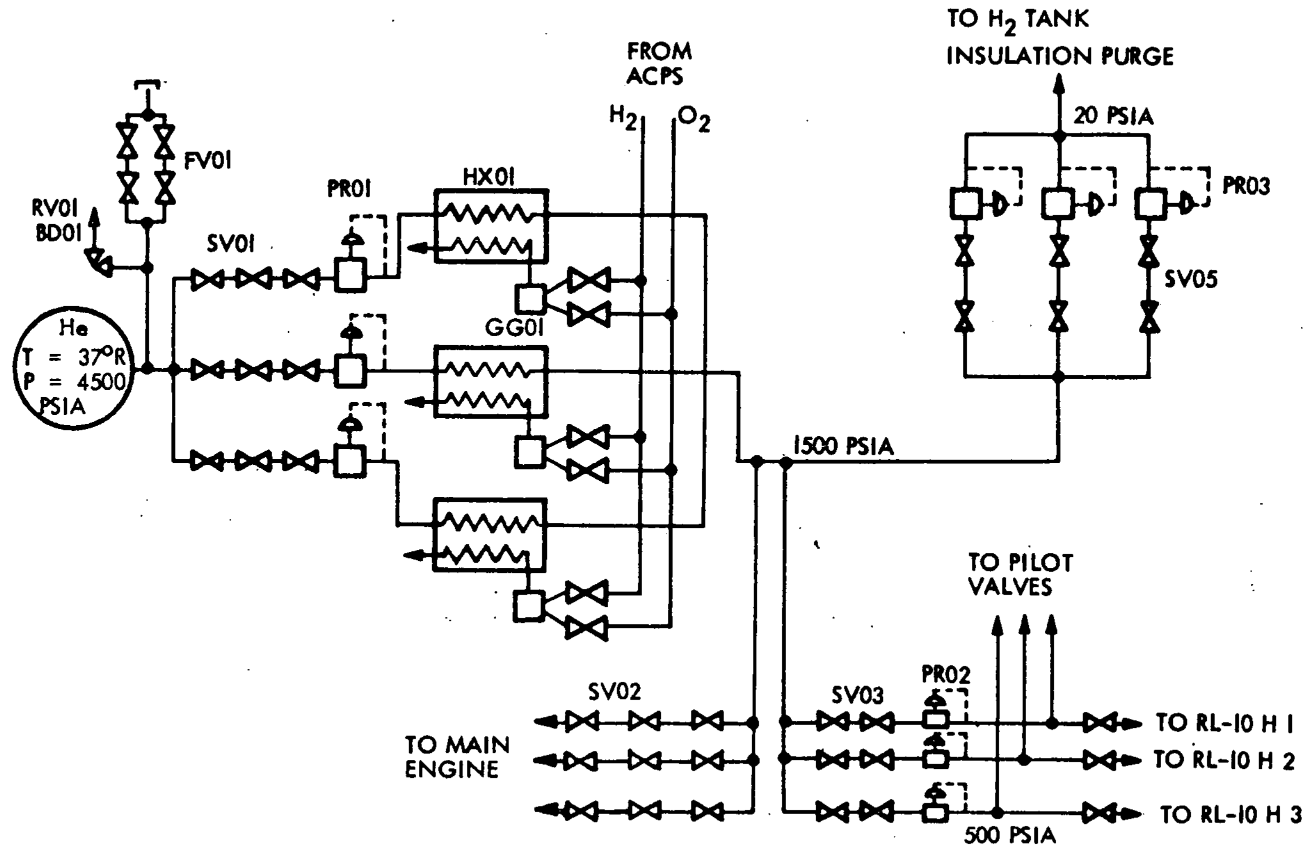


Fig. 9.7-3 Helium Stored at LH_2 Temperature

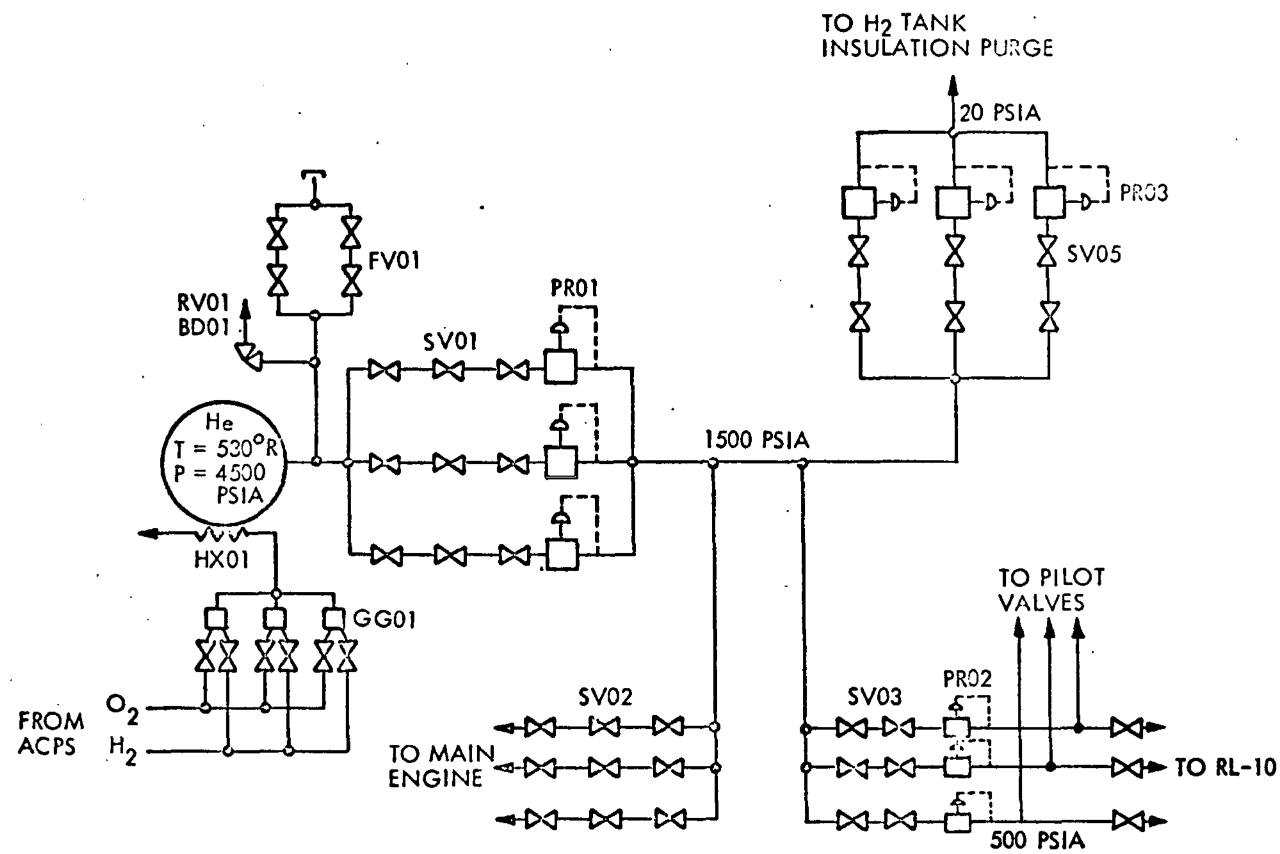


Fig. 9.7-4 Helium Stored at Ambient Temperature

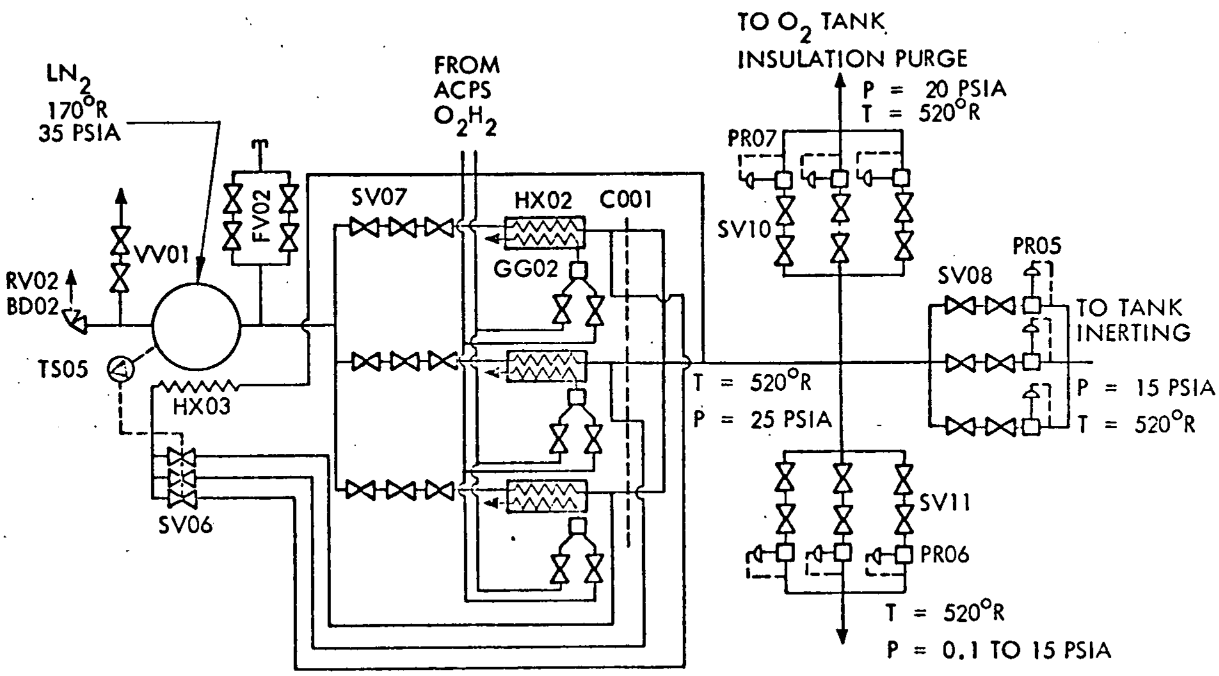


Fig. 9.7-5 Subcritical Storage of Nitrogen

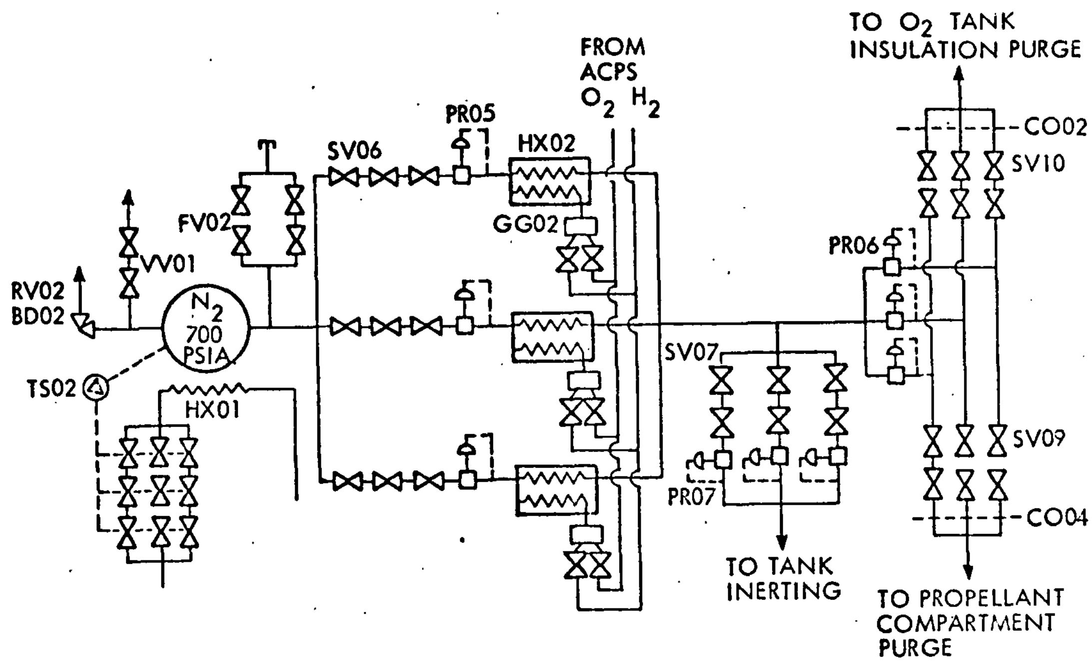
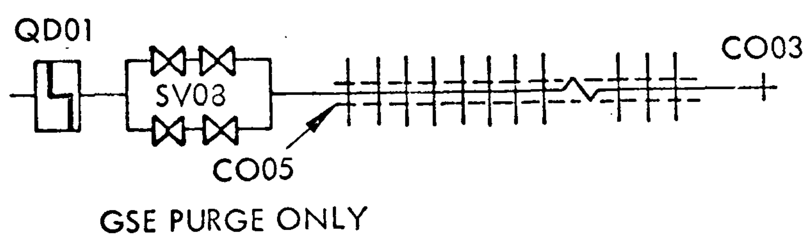


Fig. 9.7-6 Supercritical Storage of Nitrogen



(Typical for subcritical and supercritical storage of nitrogen.)

Fig. 9.7-7 Ground Purging Subsystem

9.7.2 Detailed Subsystem Analyses

The unique nature of the Purging, Inerting, and Pneumatic Supply subsystem results in most of the analyses being related to establishment of requirements as follows:

- Helium Requirements (Possible)
  - Main engine pneumatic and purging
  - RL-10 pneumatic and purging
  - Pneumatic valves
  - Hydrogen tank insulation purging
- Nitrogen Requirements (Possible)
  - Hydrogen tank inerting
  - Hydrogen purging (leakage regions)
  - Oxygen tank insulation purging
  - Airbreathing fuel oxygen removal and tank inerting

Schematics were selected to determine the leakage rates for hydrogen and the valve actuation requirements. The schematics used for the analyses are presented in Figs. 9.7-8, 9.7-9, and 9.7-10.

9.7.2.1 Main Engine Pneumatic and Purge Helium Requirements. The main engine pneumatic and purge requirements were determined from the Shuttle Engine Interface Control Document 13M 15000B, dated 1 March 1971. The requirements indicate that the helium required is approximately 20 lb per engine per mission. The minimum pressure to be supplied is 1500 psia; supply rate is 6 lb sec. The requirements are summarized in Table 9.7-1.

9.7.2.2 Orbit Maneuvering Supply Engine Pneumatic and Purge Helium Requirements. The Pratt and Whitney RL-10 engine requirements were obtained from P&W data. These RL-10 engines have been designed to employ purging on the pump seals to prevent propellant gas mixing in the gear box. It is not considered essential to maintain this purging during the entire mission, which would require 27 lb of helium. With proper valving and control, the helium loss could be lower to 1.7 lb of helium.

9.7.2.3 Pneumatic Valve Actuation Helium. Requirements for pneumatic valve actuation have been tabulated using AiResearch data for the respective components and mission duty cycles. The requirements are presented in Table 9.7-1.

9.7.2.4 Insulation Purging Helium and Nitrogen Requirements. If multilayer insulation is used outside of a vacuum jacket, purging is required during groundhold and ascent and possibly during reentry. Helium would be used for purging insulation on the hydrogen tanks and nitrogen would be used for purging of the oxygen tanks.

9.7.2.4.1 Groundhold Purging of Insulation Systems. The groundhold purging of insulation systems has the objectives of (1) preventing atmospheric contamination of the insulation and (2) keeping the external purge bag or container above some desired temperature. Groundhold and ascent purging do not require on-board gas storage since ground supply is used. The studies included consideration of keeping the purge bags temperatures above $530^{\circ}R$ to prevent water condensation and holding the temperatures above $200^{\circ}R$ to prevent oxygen condensation.

The liquid-hydrogen tank and the liquid-oxygen tank of a typical orbit maneuvering system and the liquid-hydrogen tank of the orbit injection system were examined for various annular gas flow dimensions. Predictions were made of the required purge gas flowrates, the purge-gas inlet temperatures, and the heat addition requirements to the inlet gas to keep the purge bag temperature above $530^{\circ}R$.

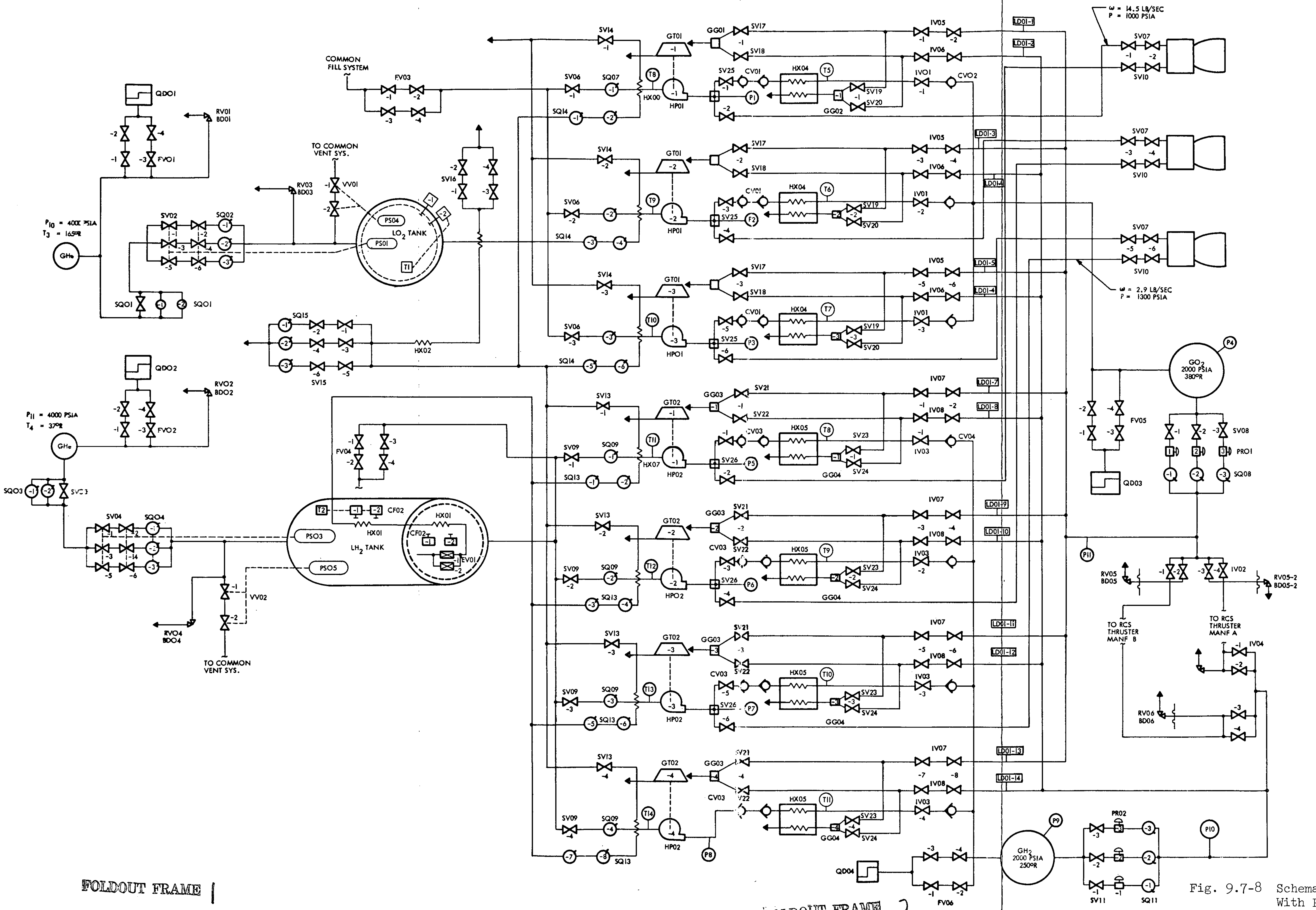


Fig. 9.7-8 Schematic for OMPS/ACPS With Pump-at-Tank

FOLDOUT FRAME 1

FOLDOUT FRAME 2

FOLDOUT FRAME 3

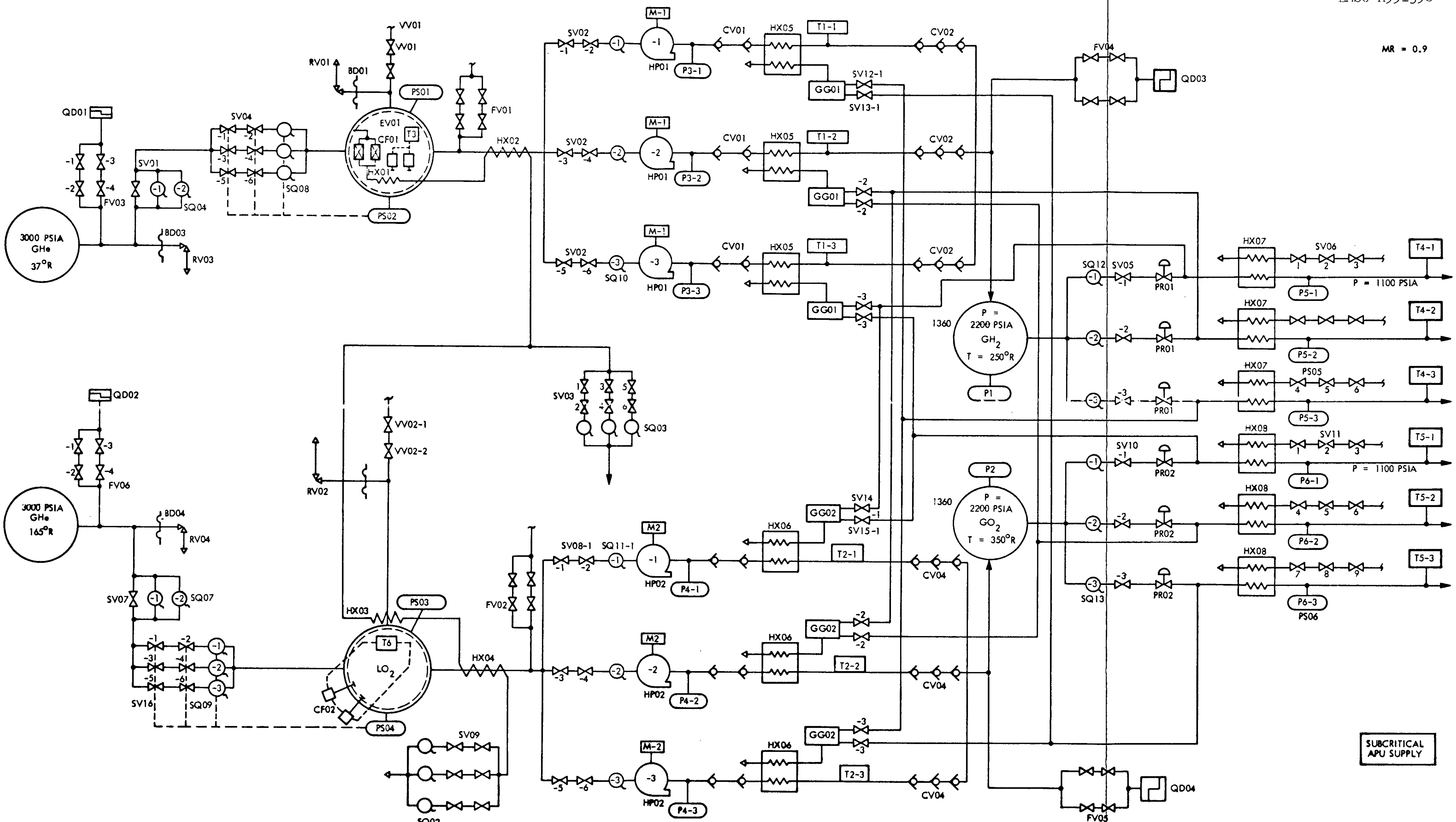


Fig. 9.7-9 Subcritical APU Cryogenic Supply Subsystem

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Table 9.7-1

PURGING, INERTING, AND PNEUMATIC SUPPLY HELIUM REQUIREMENTS

Subsystem	Function	Reentry Without LH_2 in Tanks (lb)	Reentry With LH_2 in Tanks (lb)	Pressure (psia)	Temperature (^oR)	Flowrate (lb/sec)
OIPS	Engine Pneumatic and Purge	60	60	1,500	490-600	6 (Max)
	Pneumatic Valves	5	5	1,500	490-600	0.6 (Max)
OMPS/ ACPS	RL10 Purge Pneumatic Without Continuous Bleed	1.7	1.7	470 ±30	140-620	< 0.01
	With Continuous Bleed	27	27			
	H_2 Tank Insulation Purge	1.5-3		15	520 (Inlet)	< 0.01
			10 (Inventory)	15	520 (Inlet)	0.02
	Pneumatic Valves	0.95	0.95	700	460-600	< 0.01
APU	Pneumatic Valves	0.04	0.04	700	460-600	< 0.01
Fuel Cell/ EC/LSS	Pneumatic Valves	0.35	0.35	700	460-600	< 0.01

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The data for these conditions, presented in Figs. 9.7-11 through -16, indicate that the helium would be excessive unless a closed-loop recirculation system is employed. If the gas can be put in the orbit maneuvering hydrogen-tank insulation at a temperature of $600^{\circ}R$, the gas flowrate would be 2,500 lb/hr, and the heat input 20,000 to 30,000 Btu/hr. It is interesting to note that the gas flowrate requirements are not very sensitive to the annular gas flow space, but that the heat addition requirements are sensitive.

The purging of the LH_2 orbit-injection tank would require a compressor/re-circulator of significant size.

Studies were made of the requirements for maintaining a temperature of $200^{\circ}R$ on the external surface of the purge bag or container. These studies indicated that a purge gas temperature of about $350^{\circ}R$ would exist in the annular passages with no heat addition if the ambient temperature is above $530^{\circ}R$.

Based upon the above observation that heater power is not required in the circulating gas system to hold the purge bag temperature $T \geq 200^{\circ}R$ for environment gas temperatures $T_o \geq 300^{\circ}R$, it is then obvious that purge gas circulation is not required. A closed helium purge bag could be used in this application, and this simpler purge gas system was investigated.

Figure 9.7-17 shows that the minimum required environment gas temperature T_o needed to maintain a purge bag temperature $T = 200^{\circ}R$, as a function of the purge bag outside heat transfer coefficient h_o and the annular gas spacing H. Free convection heat-transfer coefficients on the order of $h_o = 1.0$ Btu/hr ft$^{2\circ}$R require higher environment gas temperature T_o than do the higher free and/or forced convection heat-transfer coefficients expected if the tank compartment gas was circulated on groundhold. Increasing the annular spacing H tends to decrease the required environment gas temperature T_o. The positions of the H = 1.0 and 1.5-in. curves should be raised slightly due to some free convection in the annular space which was neglected in this model, but the relative positions of the curves and the positions of the H = 0 and 0.5-in. curves would remain unchanged on Fig. 9.7-17.

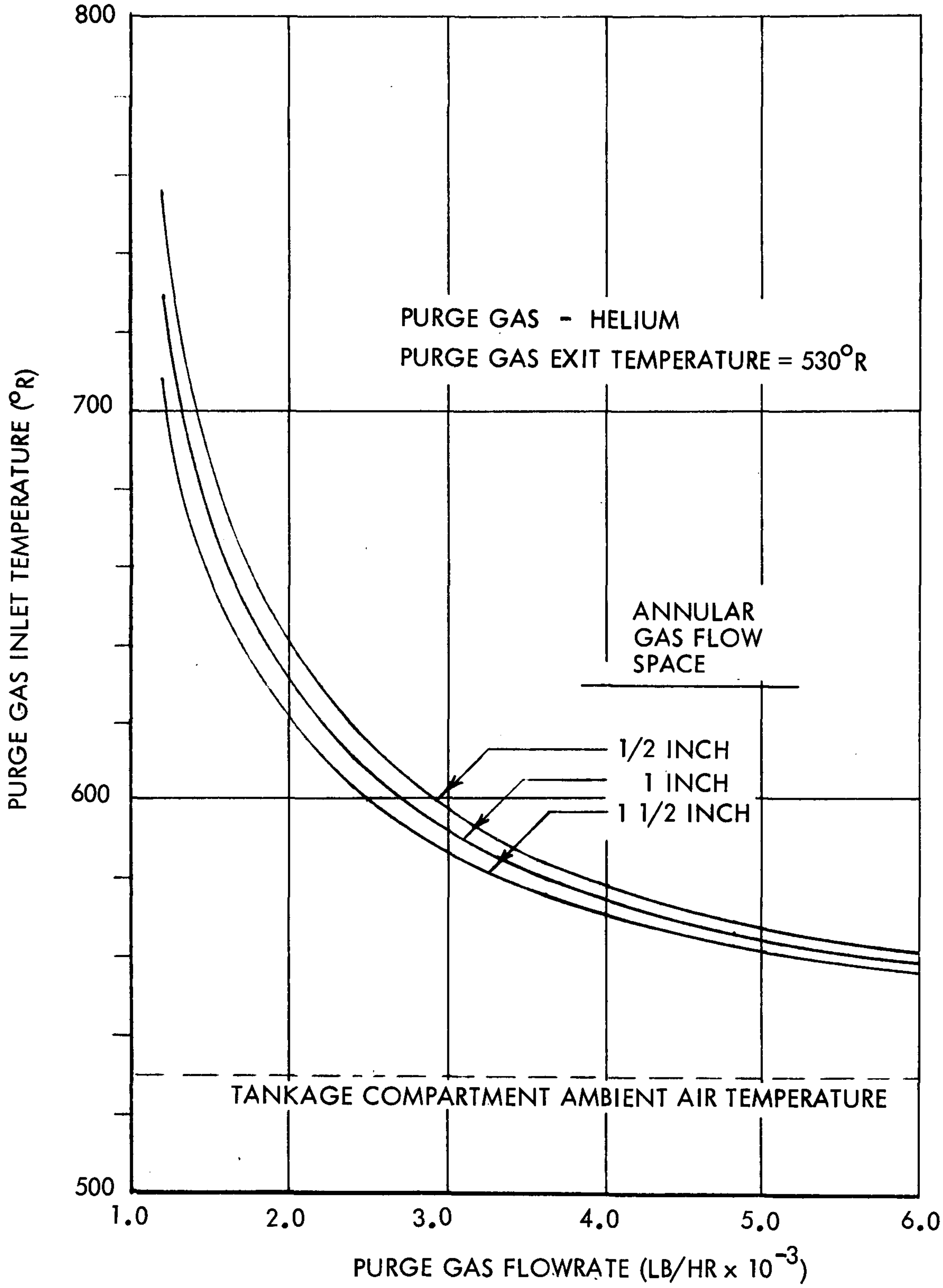

Fig. 9.7-11 OMS LH_2 Tank Ground Purging

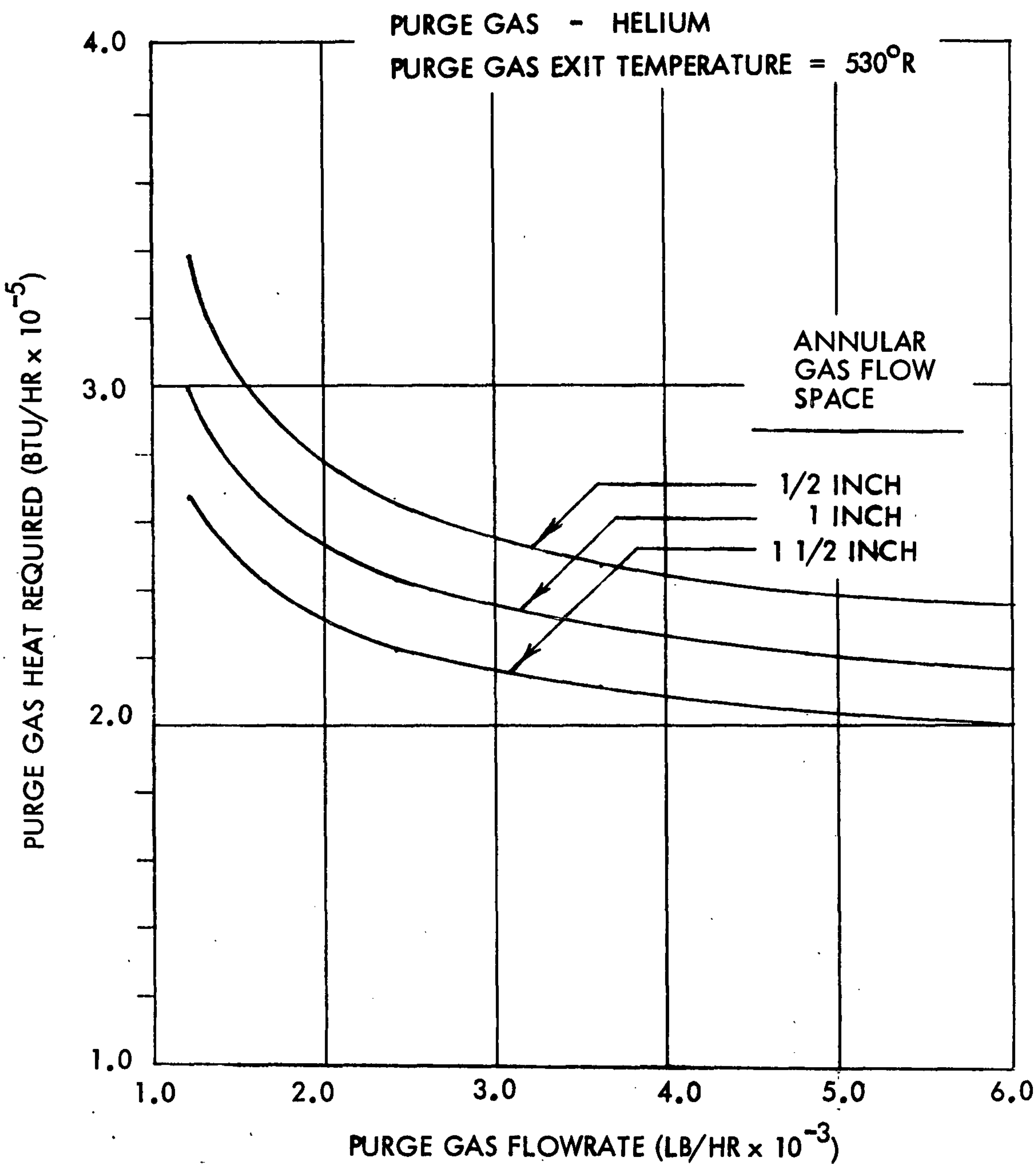

Fig. 9.7-12 OMS LH_2 Tank Ground Purging — Purge Gas Heat Requirement Vs Purge Gas Flowrate

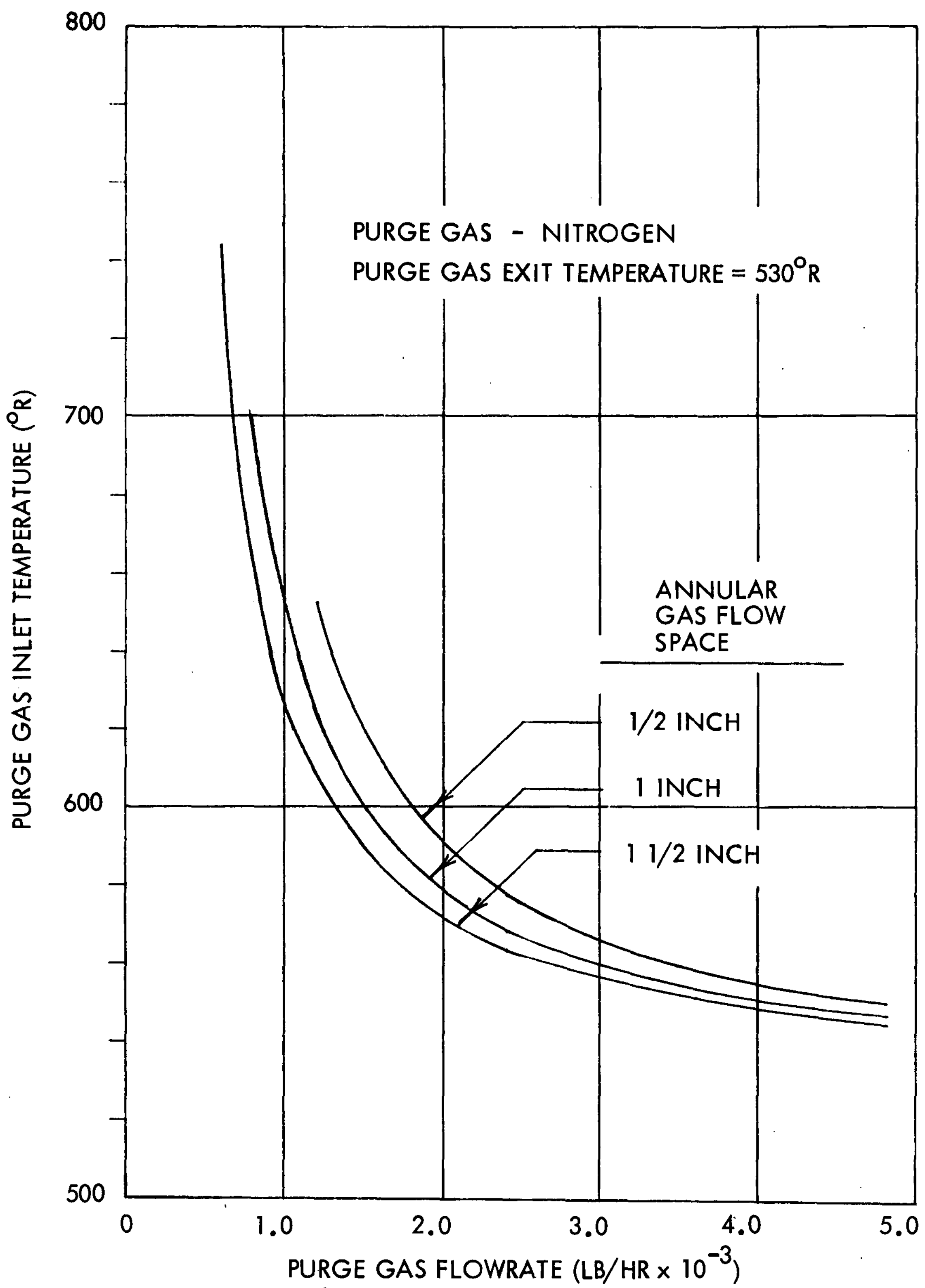

Fig. 9.7-13 OMS LO_2 Tank Ground Purging — Purge Gas Inlet Temperature Vs Purge Gas Flowrate

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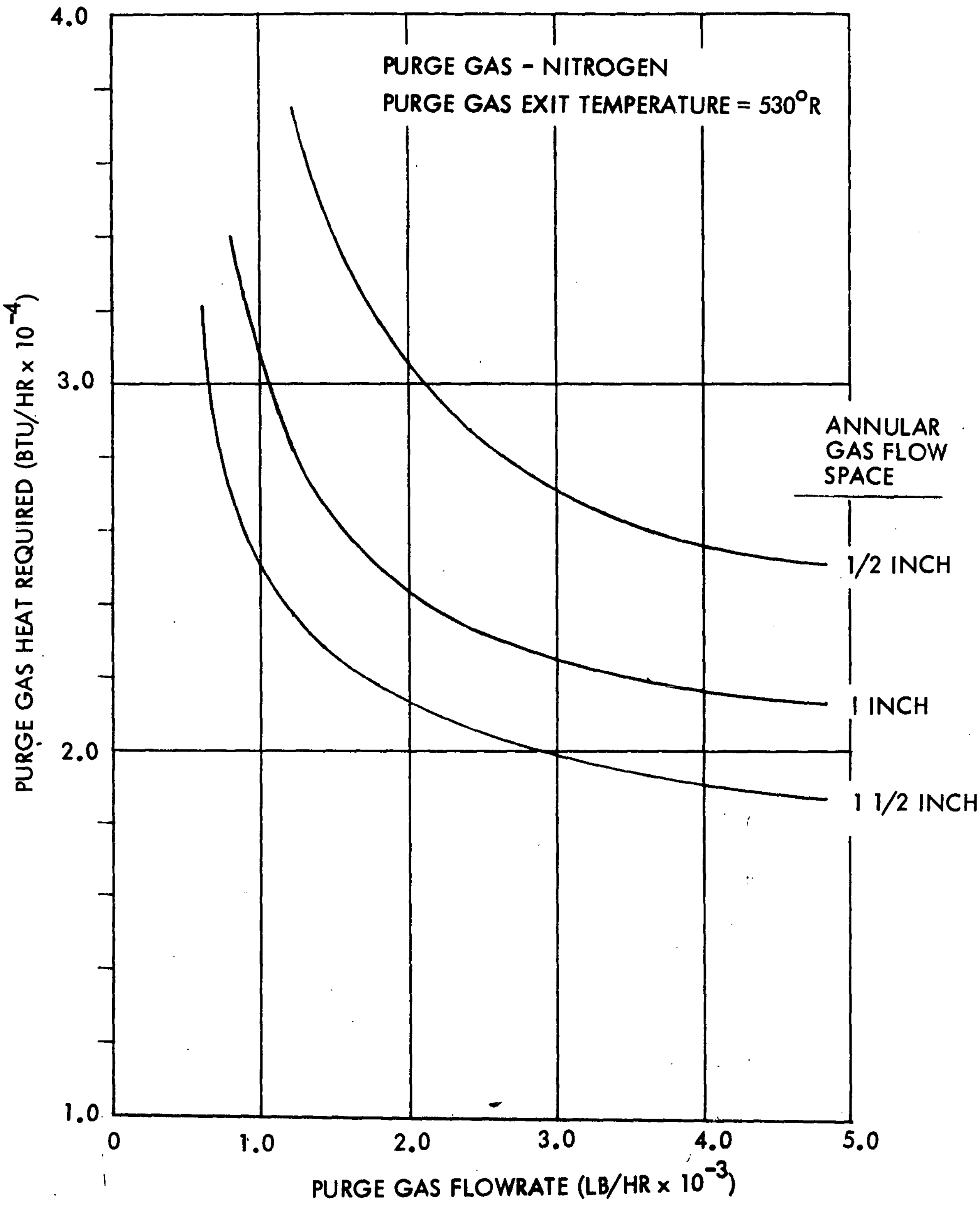

Fig. 9.7-14 OMS LO_2 Tank Ground Purging — Purge Gas Heat Requirement Vs Purge Gas Flowrate

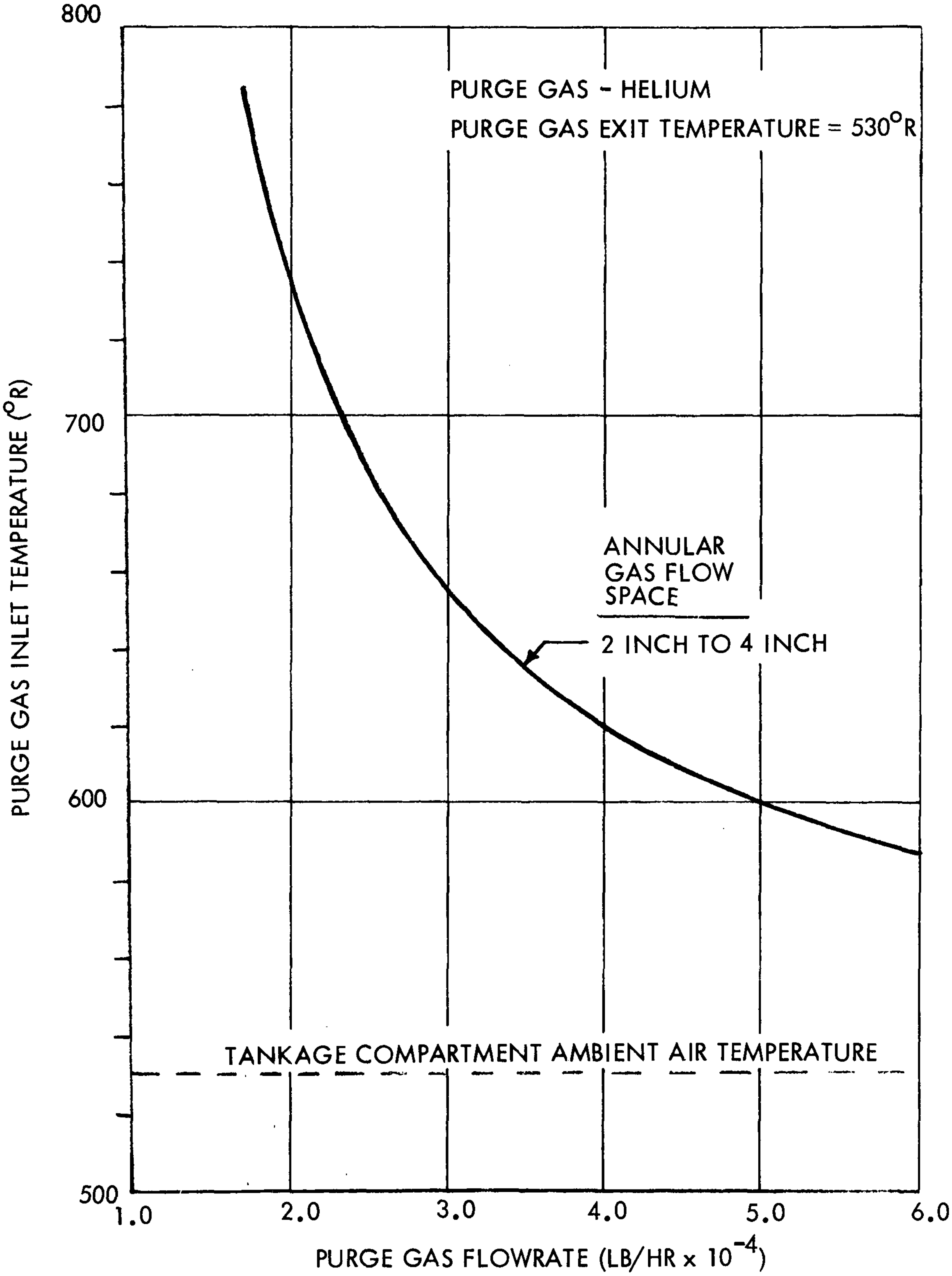

Fig. 9.7-15 Orbit Injection LH_2 Tank Ground Purging – Purge Gas Inlet Temperature Vs Purge Gas Flowrate

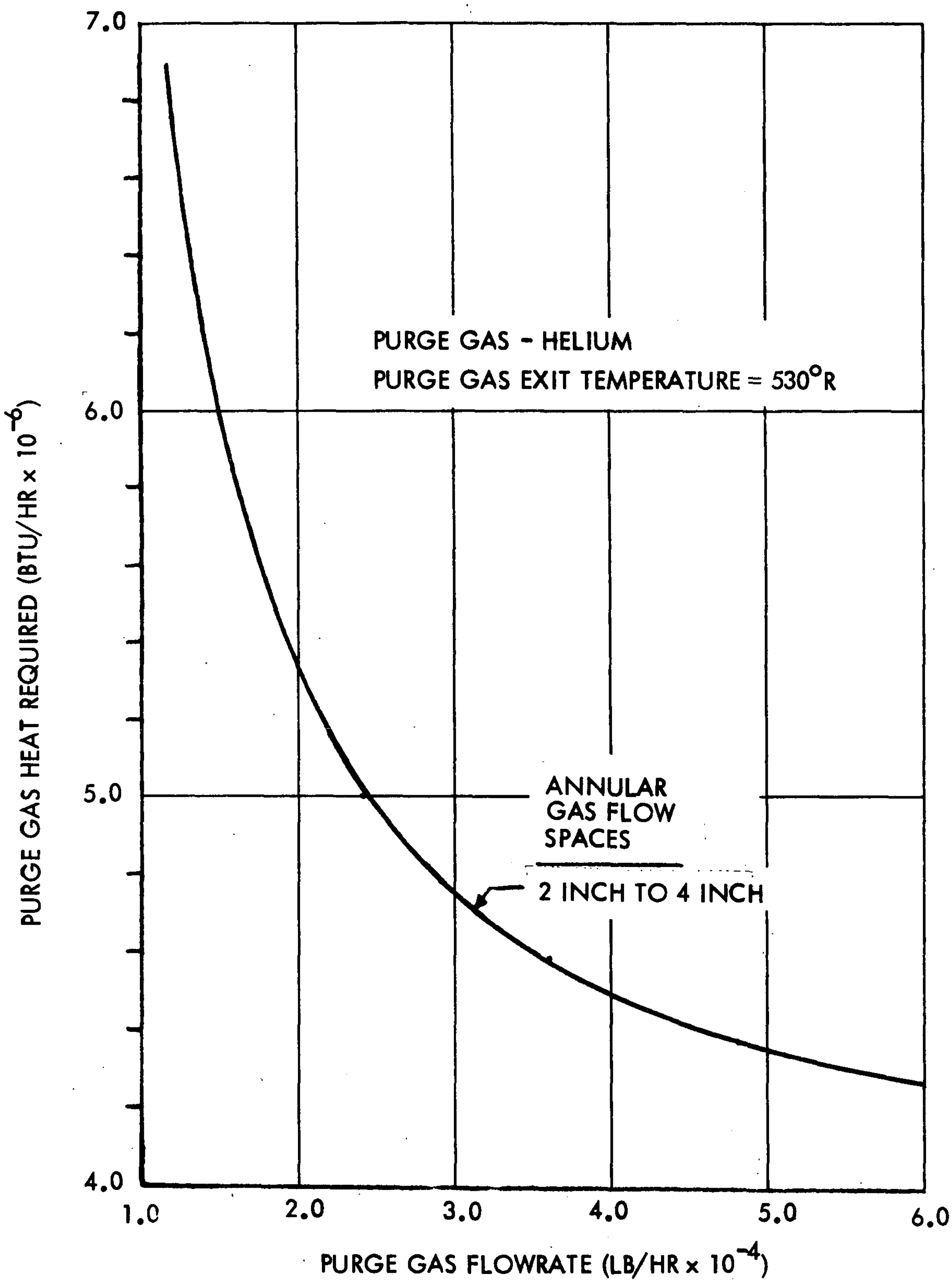

Fig. 9.7-16 Orbit Injection LH_2 Tank Ground Purging - Purge Gas Heat Requirement Vs Purge Gas Flowrate

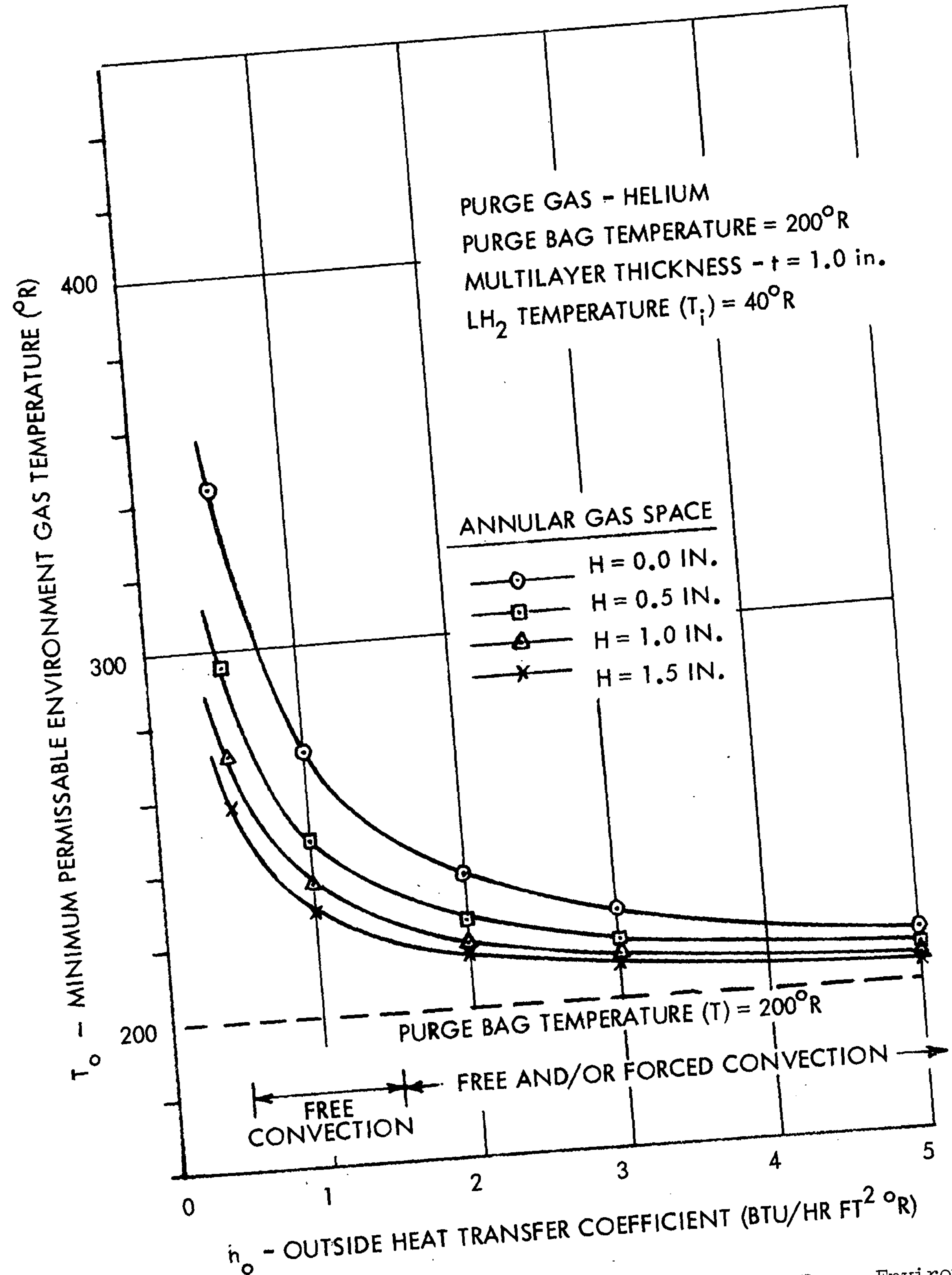

Fig. 9.7-17 OMS LH_2 Tank Ground-Purging with a Cold Bag – Environment Gas Temperature Vs Outside Heat Transfer Coefficient

Figure 9.7-18 shows the expected effect of the annular space on the heat leak per unit area into the helium-purged LH_2 tank. The solid curve shows the variation if only helium conduction existed in the annular space; the dashed curve shows the expected effect of conduction/free convection for annular spaces of $H \geq 1/2$ in. With free convection present in the annulus, the thermal resistance should be maximized and the heat rate minimized for an annular spacing of $H \approx 1.5$ in. Hence, Fig. 9.7-17 indicates that a decrease in heat leak and boiloff will result from the addition of an annular space in a closed purge bag.

The above study shows that the purge bag temperatures of $T \geq 200^{\circ}R$ should be easily obtainable with a closed noncirculating, helium purge bag system about the LH_2 OMPS tank with environment gas temperatures $T_o \geq 300^{\circ}R$. No gas heaters or flow circulation would be required for this system. The conclusions of this study should apply to any closed helium-filled purge bag system surrounding an LH_2 tank.

9.7.2.4.2 Purging of Insulation During Reentry. Insulation purging during reentry is necessary if propellants are in the tanks. Also, it is considered desirable if propellants are not in the tanks. (The alternate to purging when propellants are not in the tanks would be to employ air driers and filters, which would allow air to enter the insulation without contamination.)

The structure temperature profiles considered in the studies are presented in Fig. 9.7-19. Atmospheric data employed are shown in Fig. 9.7-20. The examinations considered were as follows:

- Purging of insulation on OMPS tanks that have been emptied prior to reentry
- Purging of insulation on OMPS tanks with liquid hydrogen in the tanks during reentry to (1) prevent water condensation and (2) prevent oxygen condensation.

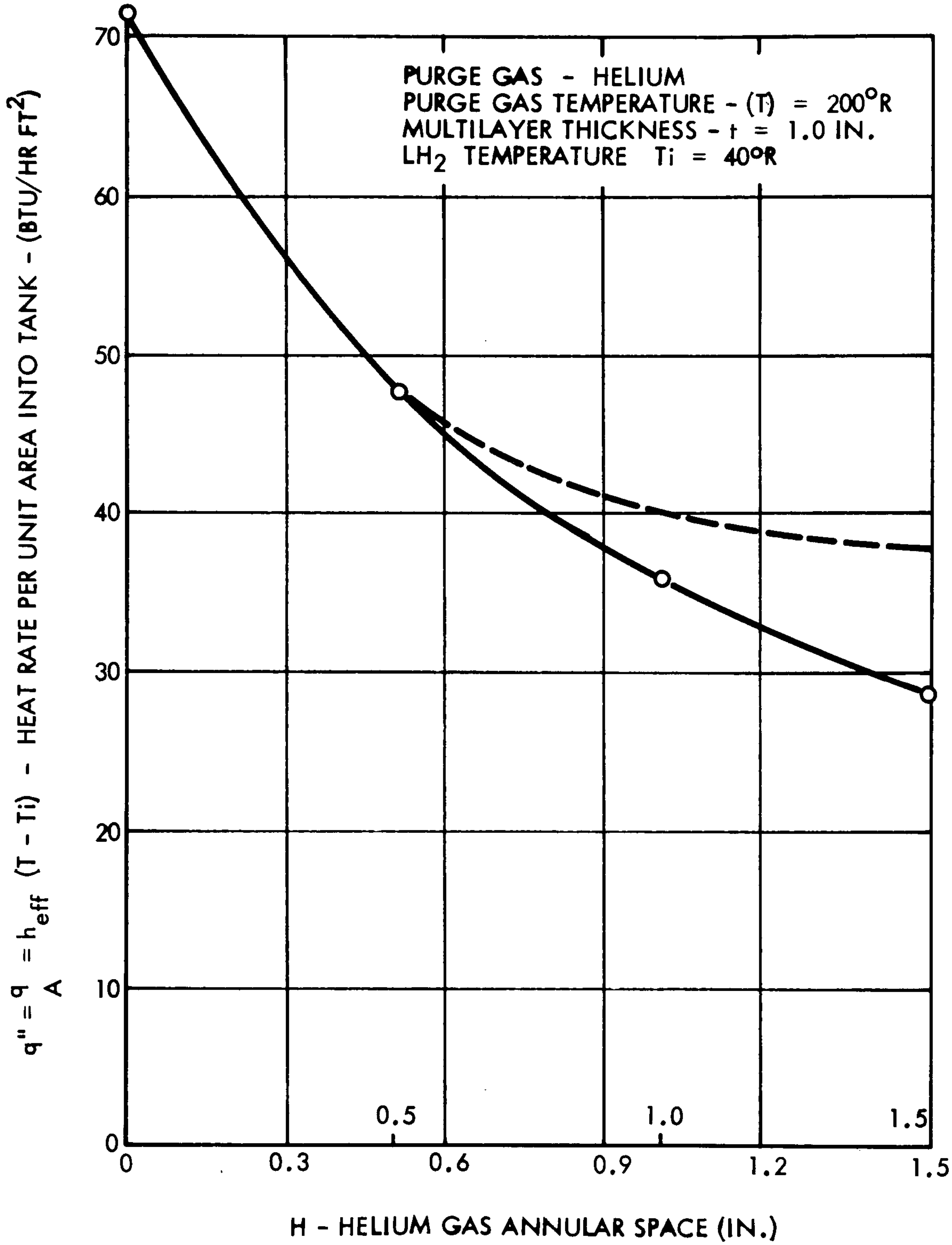

Fig. 9.7-18 OMS LH_2 Tank Ground Purging with a Cold Bag — Heat Rate per Unit Area Vs Helium Gas Annular Spacing

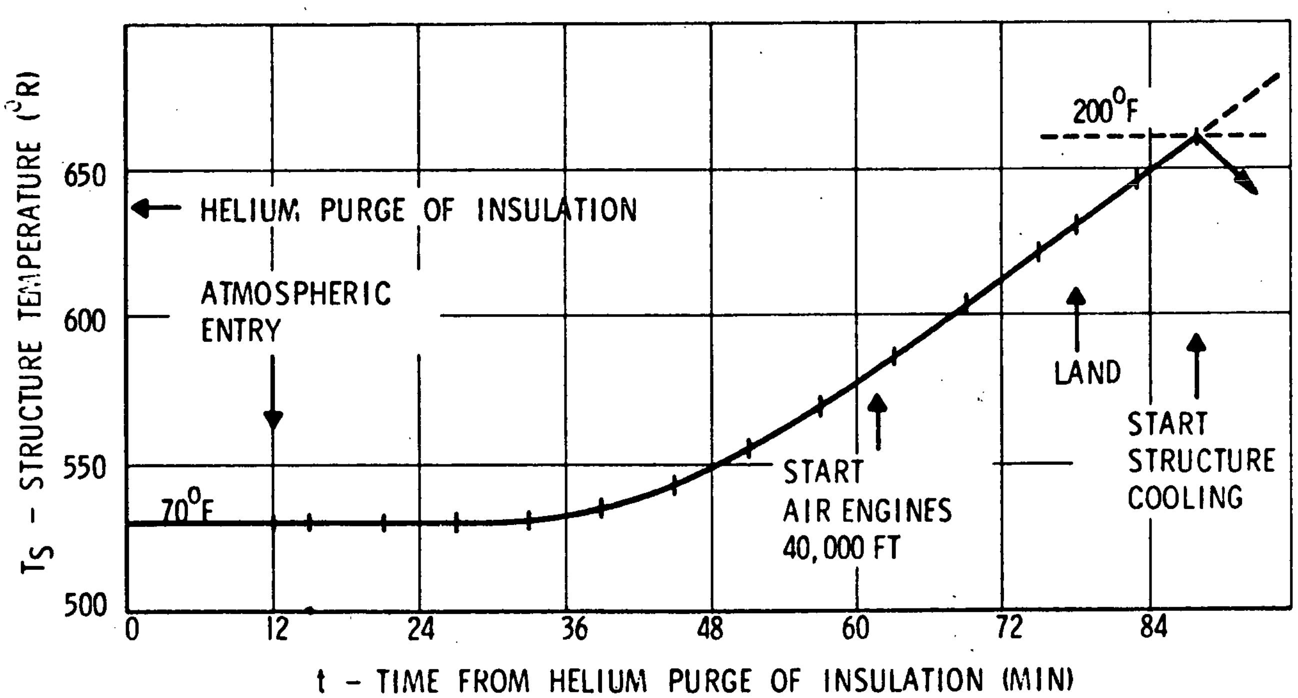

Fig. 9.7-19 Assumptions for Structure Temperature Vs Time for Reentry

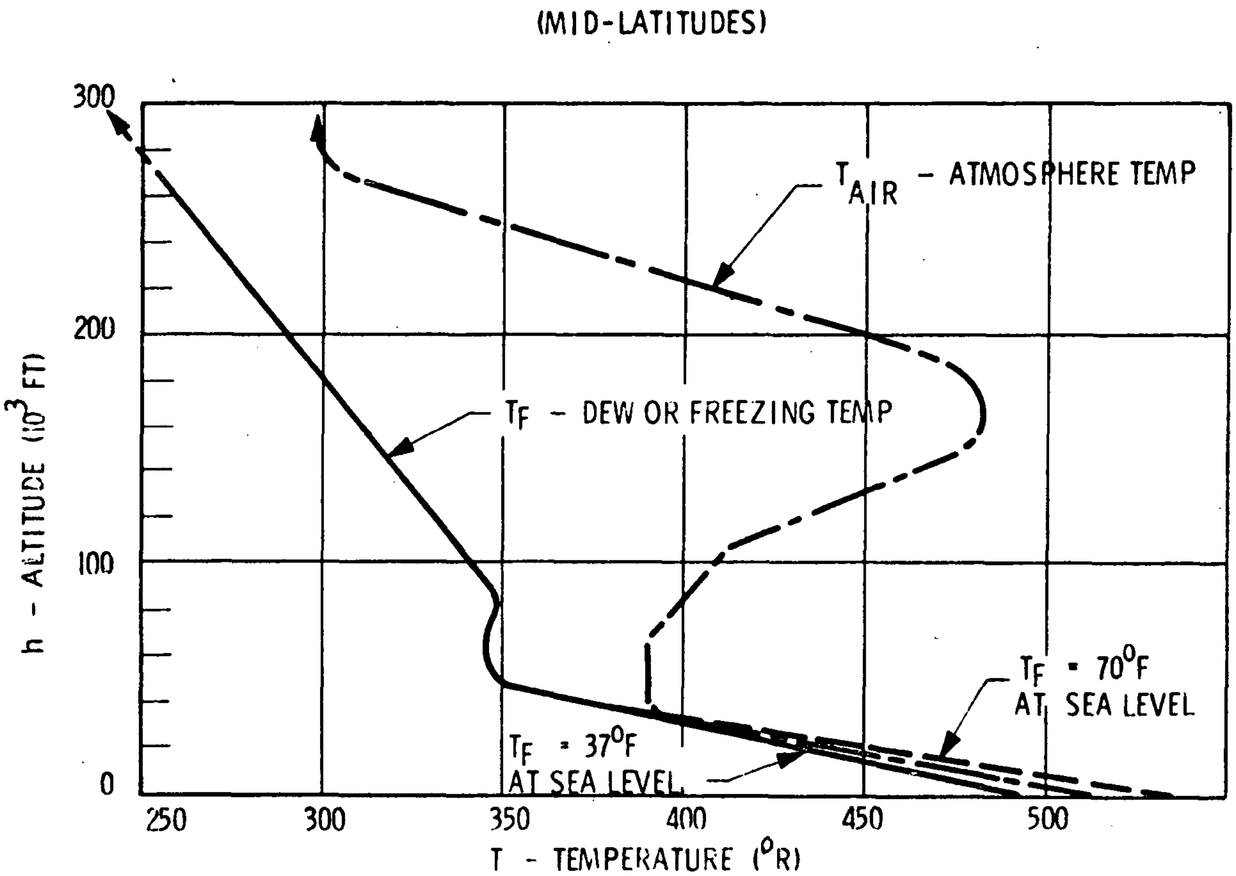

Fig. 9.7-20 Atmospheric and Dew or Freezing Temperatures for Air

9.7.2.4.3 Purging of Insulation Tanks Emptied Prior to Reentry. The evaluation of the purging of insulation on hydrogen tanks, which are emptied prior to reentry, was performed to determine if water condensation would occur on the external surface of the tanks if heat is not added. Also, the data provides valuable information in estimating the "warmup" factors associated with cold hydrogen tanks (and plumbing).

A comprehensive thermal model was constructed and analyzed. The results are presented in Fig. 9.7-21. As indicated by these data, the purge bag temperature should drop below the dew temperature and water condensation should occur.

9.7.2.4.4 Purging of Insulation on Tanks with LH_2 In the Tanks During Reentry.

Evaluations were made of the problem of maintaining a purge bag temperature above the water condensation temperature during reentry by using heated-helium in a recirculation purge. This problem is very severe, as indicated in the following discussion.

Figure 9.7-22 shows the expected structure temperature T_s and dew or freeze temperature T_f during the reentry time. Helium-gas inlet temperature T_1 to the purge bag is assumed a constant $T_1 = 600^{\circ}R$. Helium outlet temperature T_2 was initially computed as $350^{\circ}R$ and finally computed as $530^{\circ}R$. The minimum purge bag temperature T_{min} was found to be slightly higher than the gas outlet temperature T_2, so that the dewpoint temperature T_f is everywhere lower than the minimum purge bag temperature T_{min}. Dashed lines on the T_2 and T_{min} curves show a rough estimate of the expected performance during the pressure and flowrate increasing operation of the purge bag system. The helium gas flowrates were w = 378 lb/in. for the early phase and w = 1,860 lb/in. for the landing phase of operation.

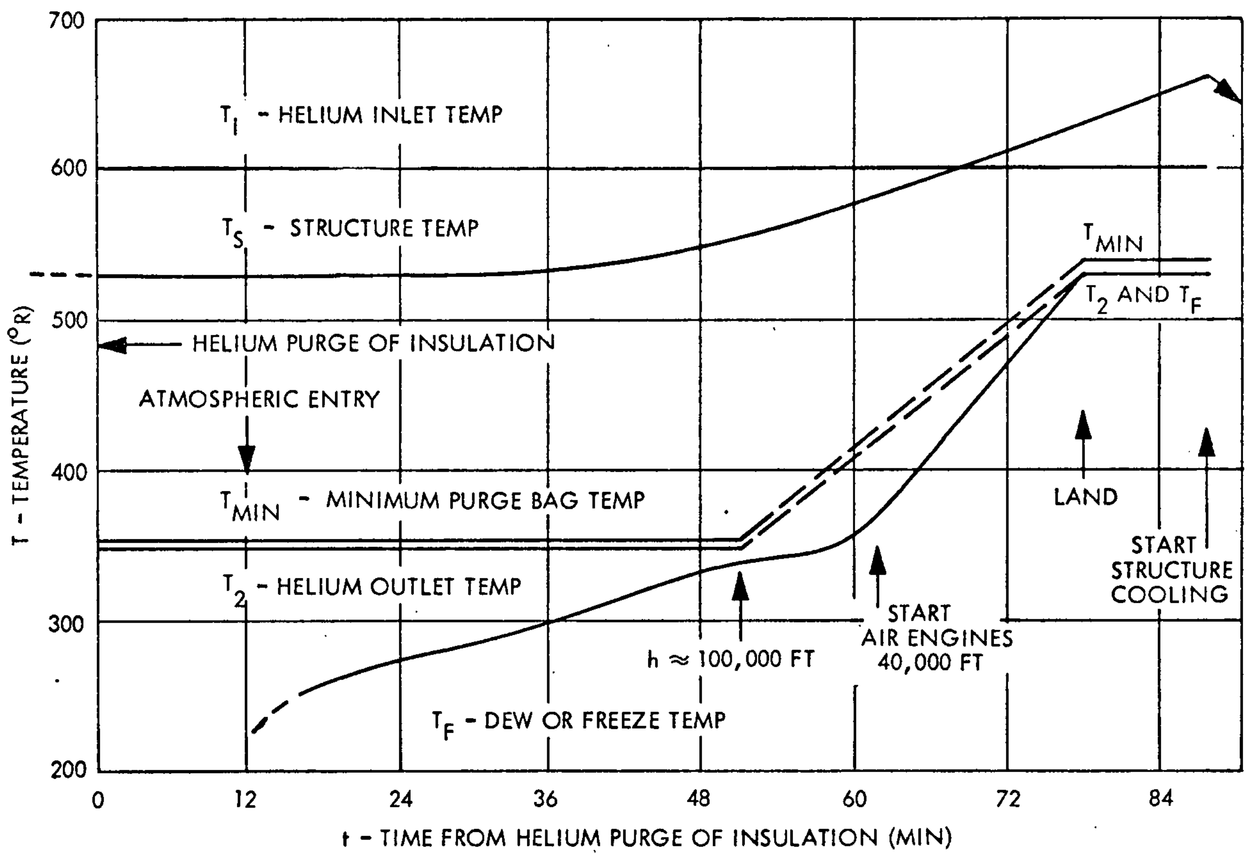

Fig. 9.7-21 Various Temperatures Vs Time From Helium Purge of Insulation

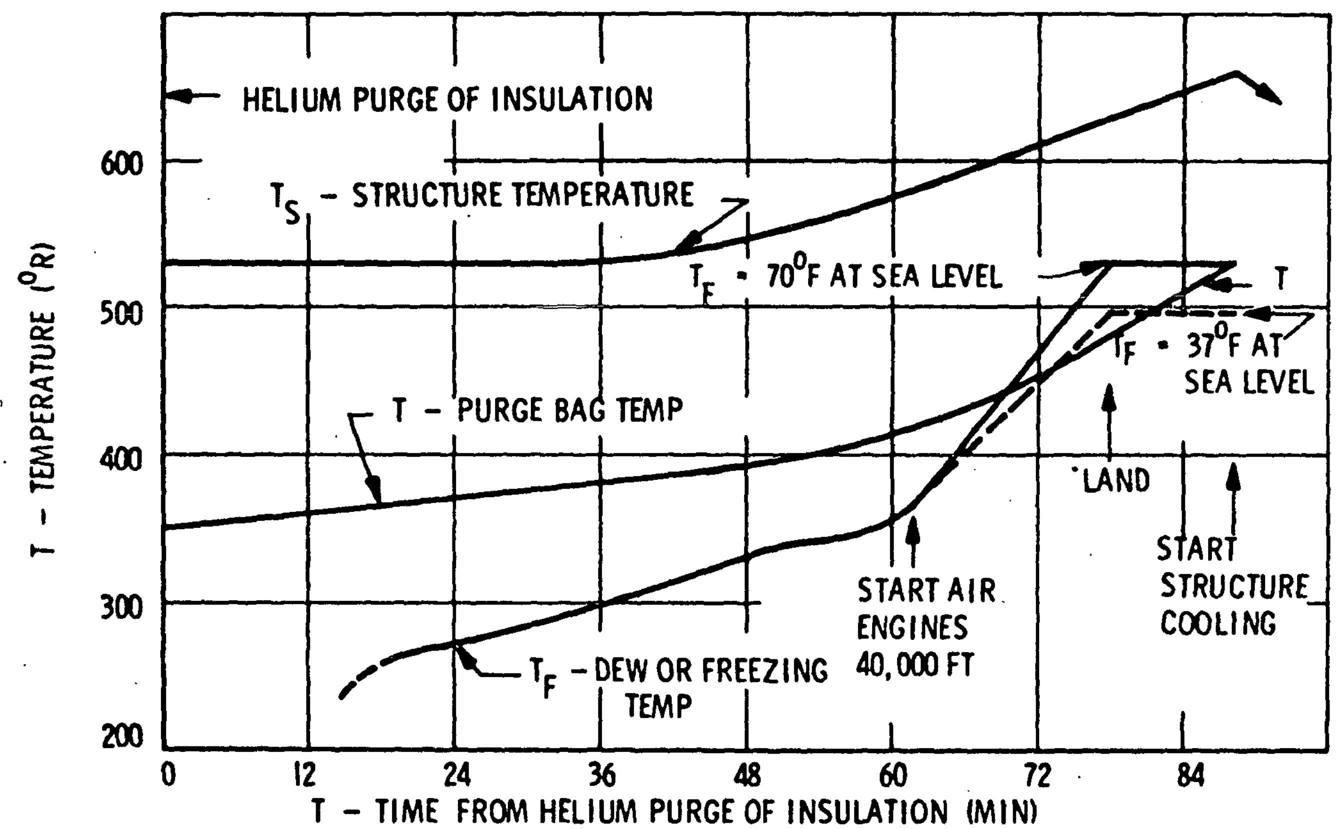

Fig. 9.7-22 Temperatures Associated with Reentry of LH_2 OMS Tank Emptied After Retro

Figure 9.7-23 shows the expected helium heater heat-transfer rate q_H and the heat leak into an LH_2 OMPS tank q_i as a function of time during reentry (with the dashed lines representing an estimate). Integration under the heat leak q_i curve results in a total heat leak of Q_i = 206,600 Btu for the total time span of 88 minutes shows for the reeentry mission. If the heat leak during the landing phase is neglected, then a total leak of Q_i = 172,800 Btu would occur to the tank. In either case, this order-of-magnitude of heat leak during reentry would require from 850 to 1,000 lb of LH_2 boiloff to maintain the tank pressure.

For the early phase of reentry, with low-pressure gas circulation at 0.5 psia, the required flowrate is 15,200 ft/^{3}min. During the landing phase, at the highest pressure of 15 psia, the required circulation flowrate is 3,140 ft^3/min. These are considered to be excessive conditions.

Analyses were made of the less severe problem of keeping the purge bag external temperature above 200°R during reentry to assure no condensation of oxygen. A comprehensive thermal model was examined. Figure 9.7-24 provides parametric data regarding the heat leaks to the tank, helium flow-rate, and helium heater rates.

Figure 9.7-25 summarizes the results of the analyses to maintain the purge-bag outside temperature above 200°R. During the first hour (57 minutes) of reentry, heated helium would have to be circulated through the purge bag. After the end of one hour, or at approximately 70,000-ft altitude, the helium gas circulation can be stopped. The heat leak to the hydrogen tanks drops significantly when heated recirculation purge is terminated and then increased again during descent.

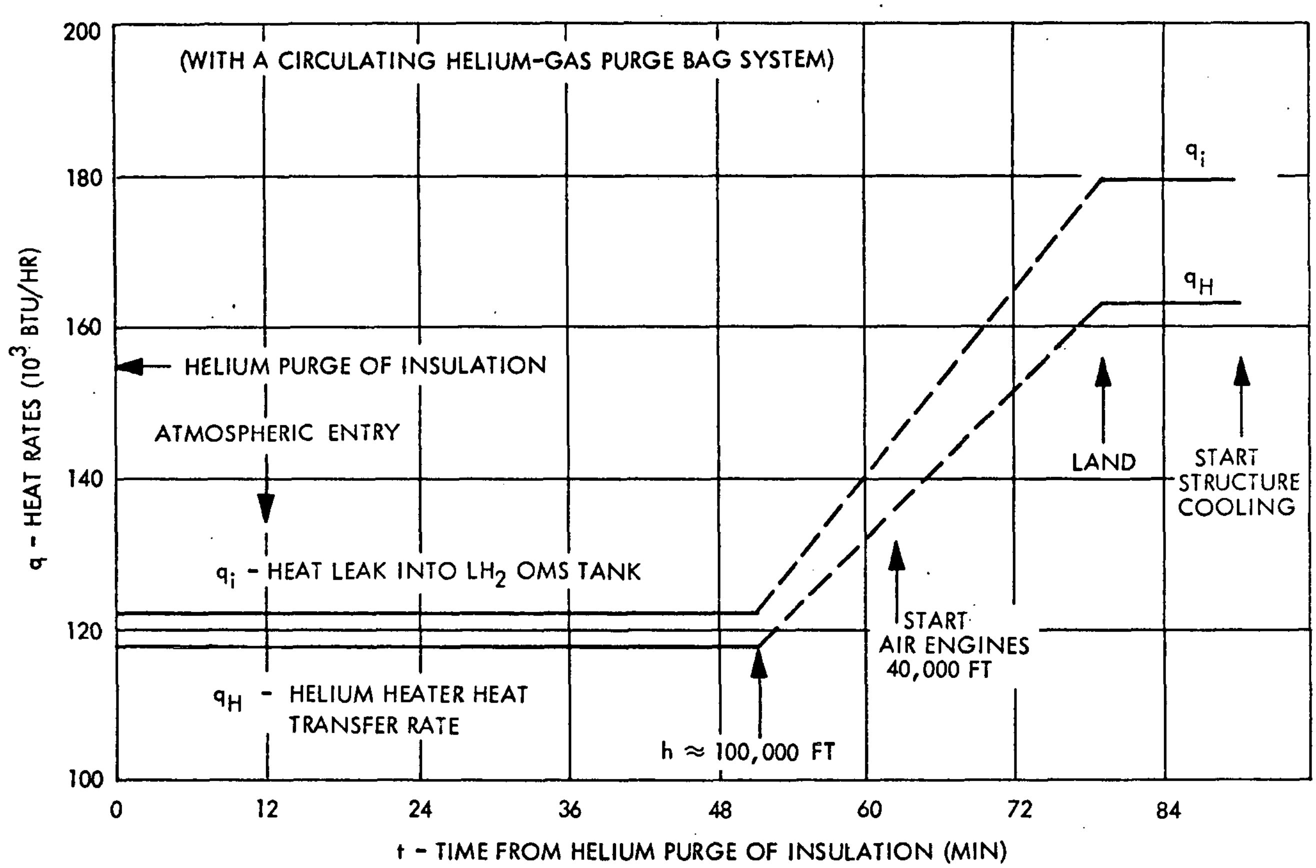

Fig. 9.7-23 Helium Heat Transfer Rate and Heat Leak Into LH_2 OMPS Tank Vs Time for Liquid Reentry

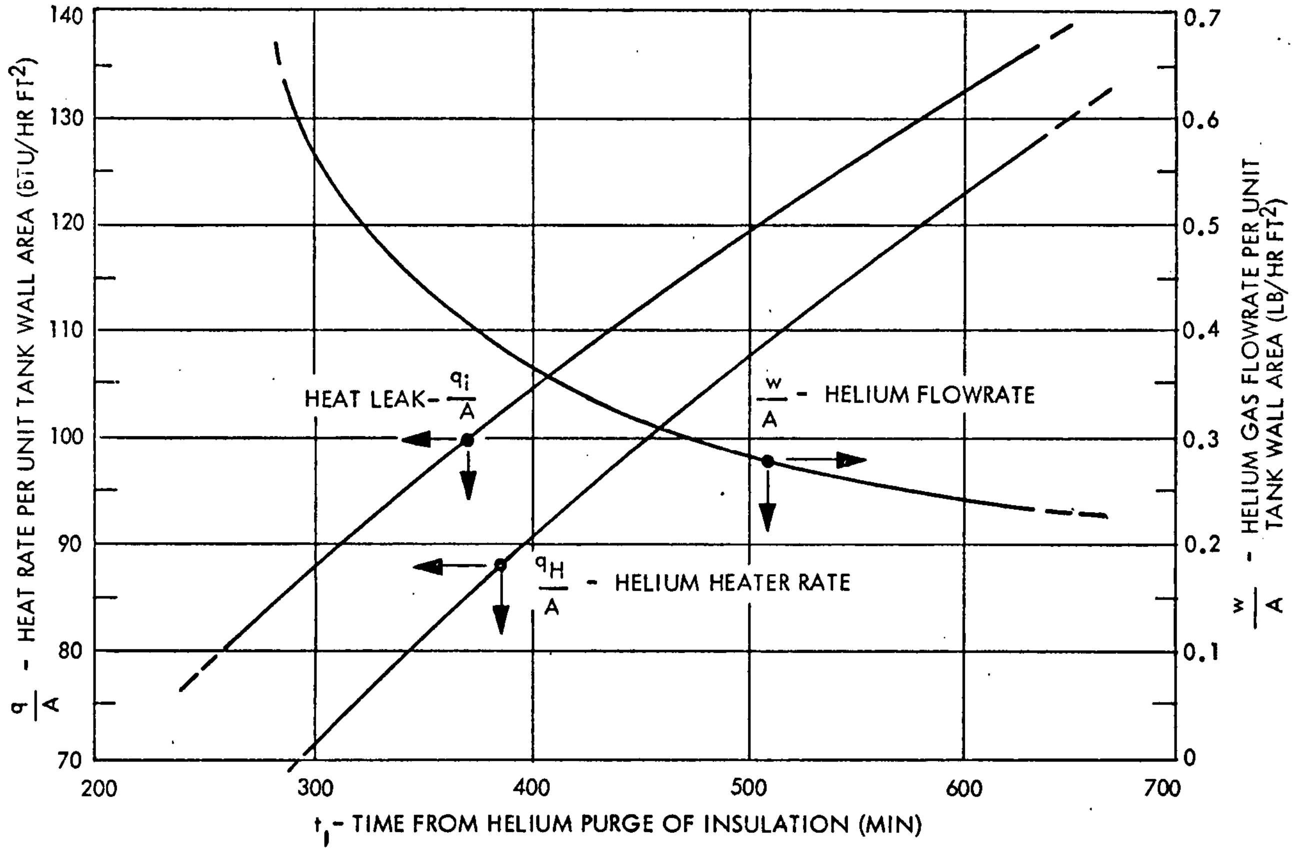

Fig. 9.7-24 Helium Heat Leak, Heater Rate, and Flowrate Vs Helium Gas Inlet Temperatures

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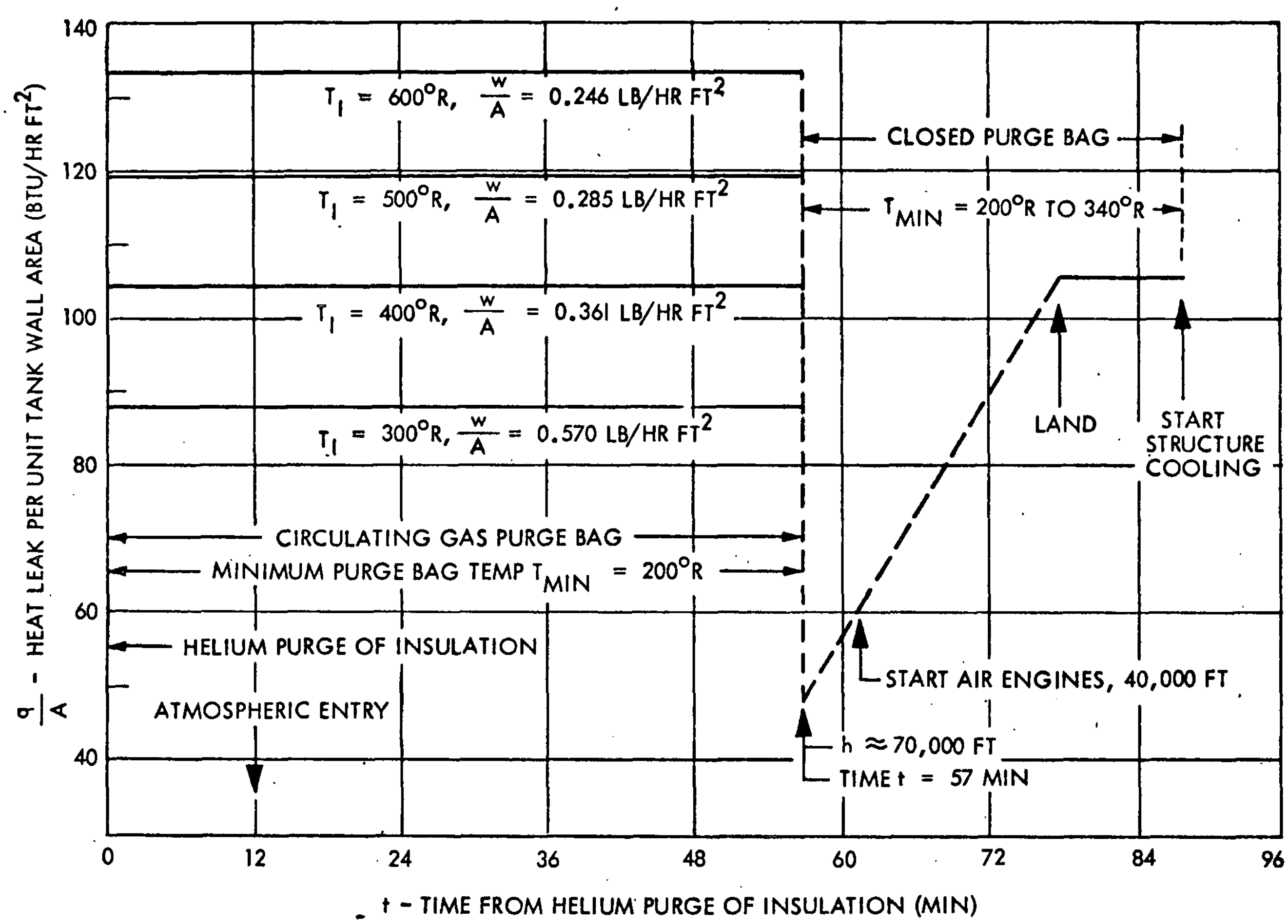

Fig. 9.7-25 Heat Leak Per Unit Area Vs Reentry Time for LH_2 Tanks with 1.0-in. Insulation

These studies indicate that tanks reentering with liquid hydrogen in the tanks must have a heated recirculation purge or some other means of increasing purge by temperature. The other possible methods are:

- Electrical-heater exterior to purge bag
- Use of foam insulation to increase resistance. (This is discussed in the component evaluations.)

9.7.2.5 Purging of Hydrogen Leakage Areas with Nitrogen. It is considered desirable from the standpoint of safety to purge leakage areas to keep the mixture of hydrogen and air below flammability limits. The data generated are presented in Fig. 9.7-26 for the nitrogen purge-gas requirements as a function of expected leakage in SCCMs. These data can be applied to the expected subsystem leakage to estimate the nitrogen purge-gas requirements.

The schematics presented in Figs. 9.7-8, 9.7-9, and 9.7-10 were used as a basis for estimating leakage requirements. Data from the AiResearch subcontract were utilized.

Estimated nitrogen requirements are presented in Table 9.7-2.

9.7.2.6 Hydrogen Tank Inerting. Hydrogen tank inerting was examined for two subsystems:

(1) Orbit Maneuvering Propellant Supply and (2) Orbit Injection Propellant Supply. Tank inerting was examined only to provide data for the tradeoff studies. (The alternative to tank inerting is considered to be purging of leakage areas as previously presented.)

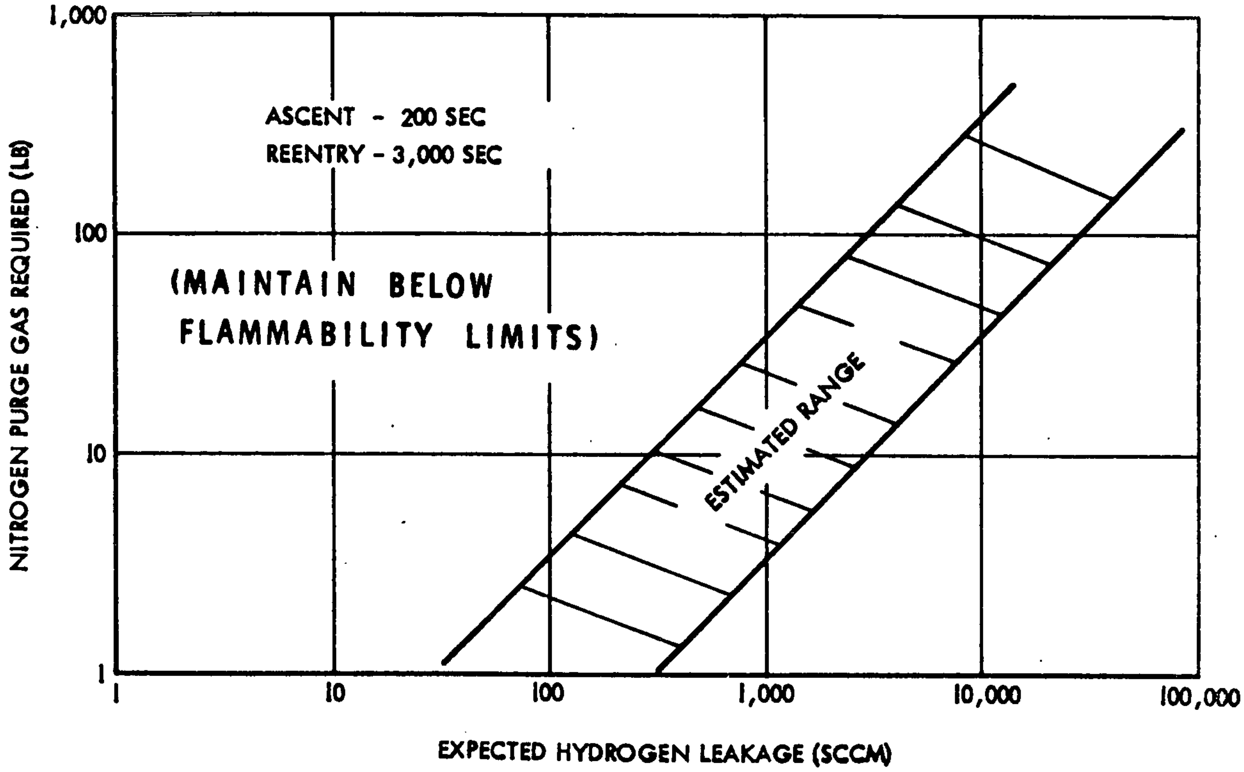

Fig. 9.7-26 Nitrogen Purging Requirements for Component Hydrogen Leakage

Table 9.7-2

PURGING, INERTING, AND PNEUMATIC SUPPLY NITROGEN REQUIREMENTS

SUBSYSTEM	FUNCTION	WITHOUT TANK INERTING (LB)	WITH TANK INERTING (LB)
ORBIT INJECTION PROPULSION SUPPLY	TANK INERTING		1,820
	LEAKAGE PURGING	1,230	340 (ASCENT)
OMPS/ACPS	TANK INERTING		150
	LEAKAGE PURGING	66	35
	OXYGEN INSULATION PURGING	4	4
APU	LEAKAGE PURGING	13	-
FUEL CELL/ECLSS	LEAKAGE PURGING	10	-
AIRBREATHING ENGINE	O_2 REMOVAL	-	0.5
	TANK INERTING		10

9.7.2.6.1 Orbit Maneuvering Propellant System Tank Inerting. OMPS tank inerting studies were conducted for tanks that were hot-gas pressurized. It was assumed that the tank would be evacuated after retroburn by dumping the liquid through engine vents and then venting the tank to vacuum, followed by nitrogen or helium inerting.

The study assumes the following chronology of events and conditions:

a. The tank, initially cold-soaked at $40^{\circ}R$, contains only a partial supply of LH_2. The insulation cold-boundary temperature is $40^{\circ}R$ and hot-boundary temperature is $520^{\circ}R$.

b. Pressurized hydrogen gas at a temperature of $350^{\circ}R$ was employed in the final deorbit burn.

c. At the termination of deorbit burn, the tank temperature is assumed to follow a linear gradient from a temperature of $40^{\circ}R$ at the LH_2 outlet end to $350^{\circ}R$ at the opposite end.

d. After deorbit burn, the tank is evacuated, with no net effect upon the bulk mean tankwall temperature.

e. Inerting gas is admitted into the tank until the tank is filled at the delivered temperature and pressure.

Parametric tank pressure history data, presented in Figs. 9.7-27 and 9.7-28, indicate that if the tanks are pressurized to the desired pressure at a lower temperature, the pressure will decay, but will recover during reentry.

The weight of nitrogen to inert an OMPS tank (nonintegrated) as a function of nitrogen temperature is shown in Fig. 9.7-29. If the final desired pressure is above 20 psia, the inerting nitrogen requirement is approximately 175 lb.

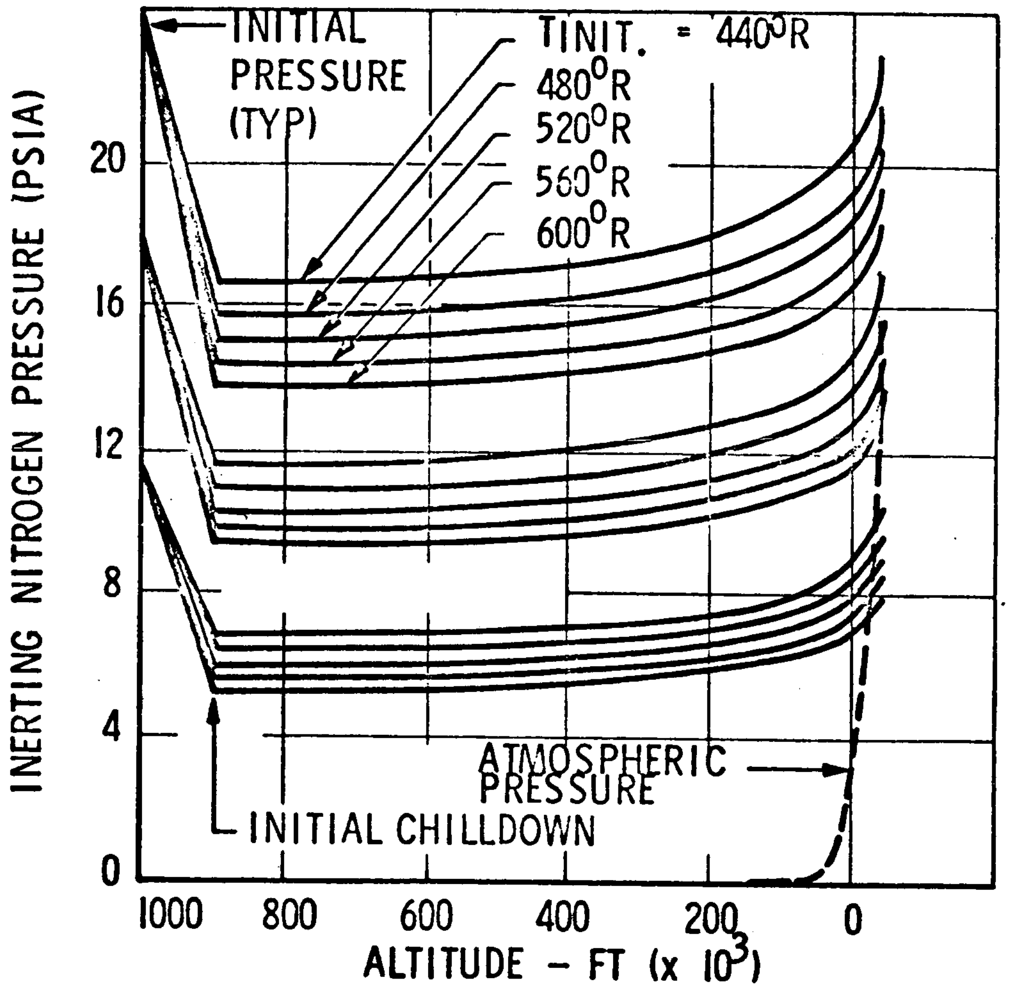

Fig. 9.7-27 Empty OMS LH_2 Tank Inerting Nitrogen Pressure History After Retro-Maneuver

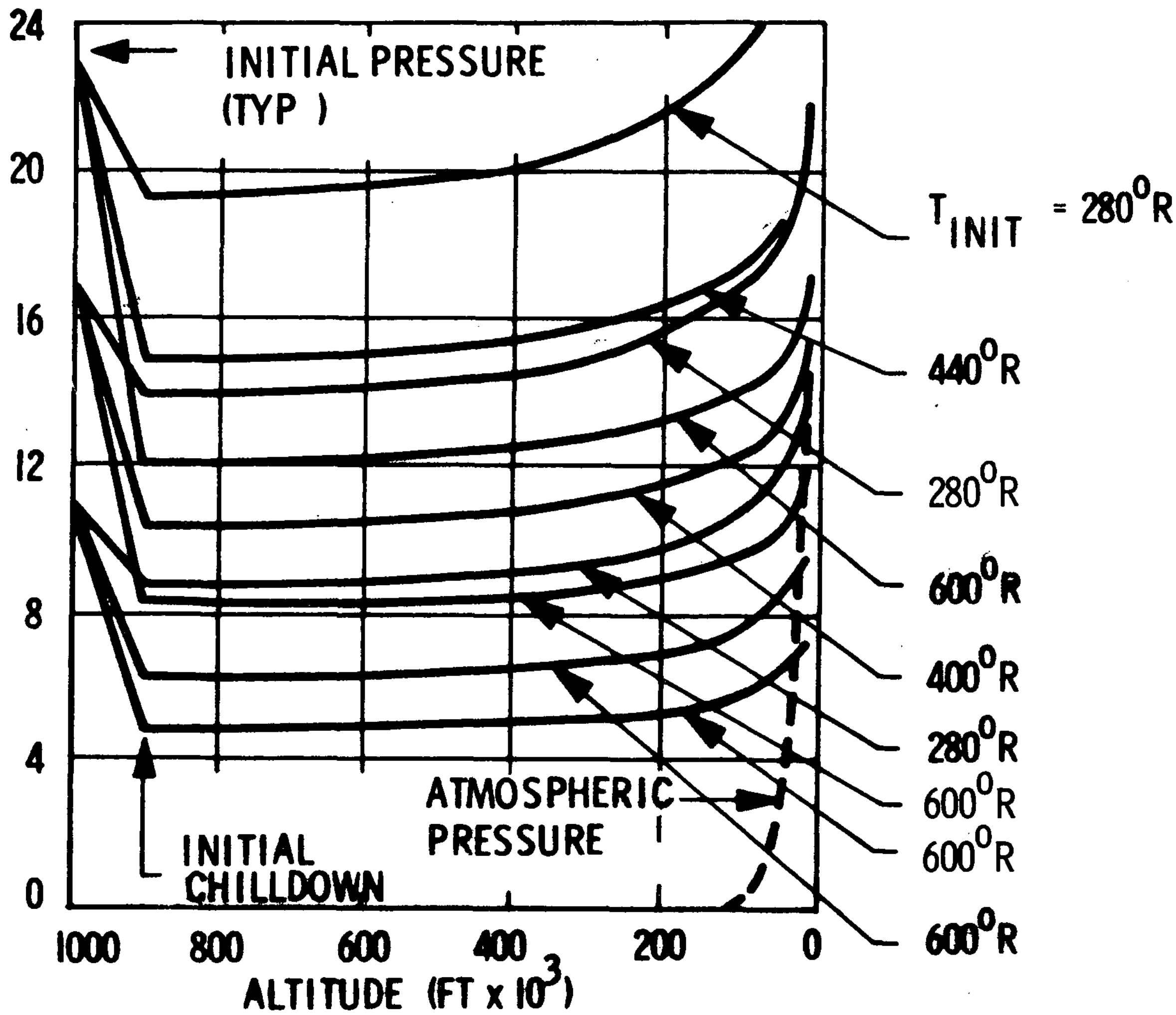

Fig. 9.7-28 Empty OMS LH_2 Tank Inerting Helium Pressure History After Retro-Maneuver

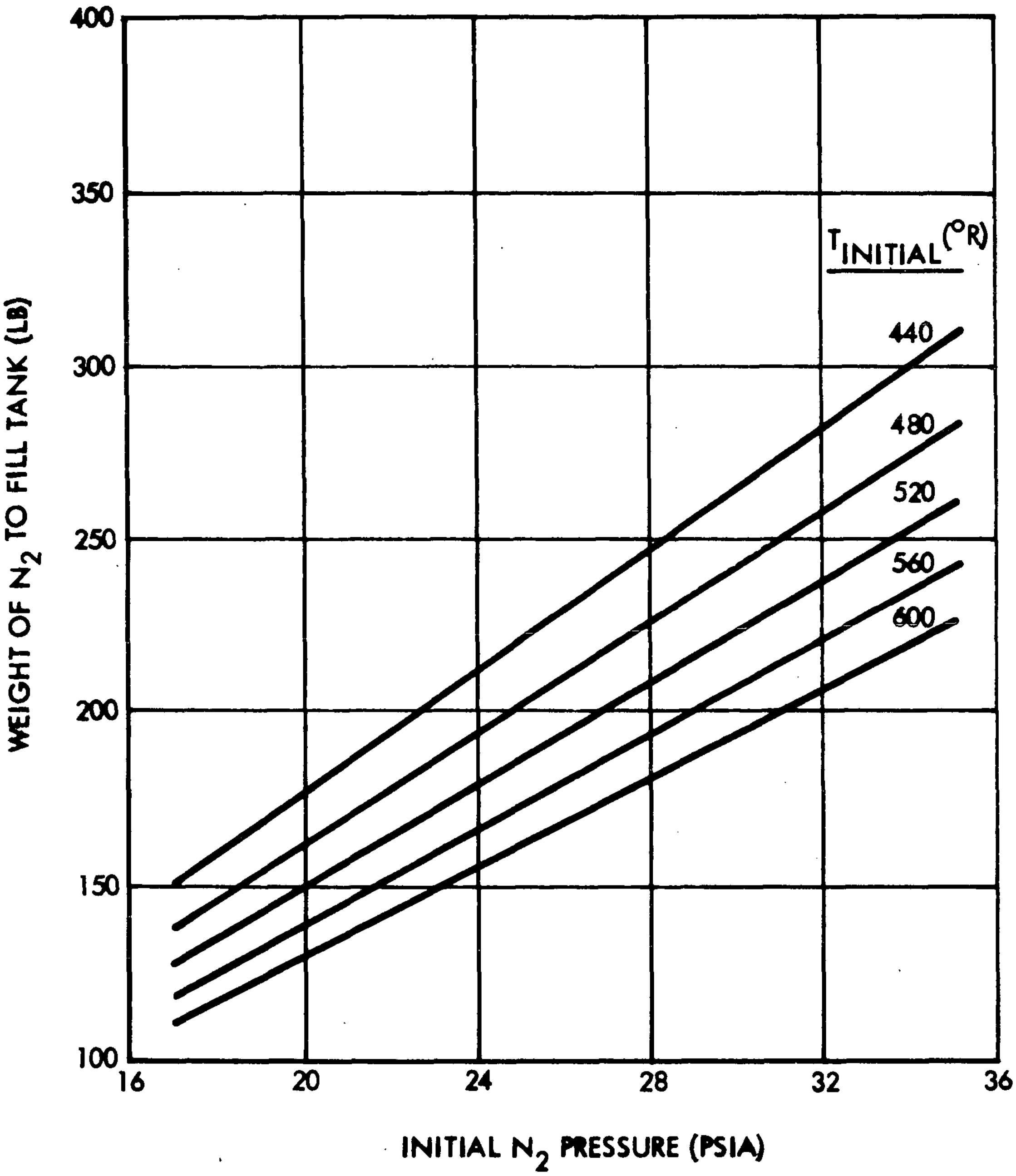

Fig. 9.7-29 OMS LH_2 Tank N_2 Inerting Gas Tank Pre-Warmed by Pressurizing H_2

The weight of helium required to inert the OMPS tank to a desired pressure of 20 psia would be approximately 30 lb as shown in Fig. 9.7-30. However, the inert weight required for storage will make total weight very close to the requirement for nitrogen inerting.

9.7.2.6.2 Orbit Injection Propulsion System Tank Inerting. The case examined for OIPS tank inerting assumed that (1) the liquid in the tanks is drained through the engine vents, (2) the tank is allowed to come to space equilibrium during the mission, and (3) venting and inerting follow prior to reentry. The requirements for the McDonnell-Douglas Orbiter are presented in Table 9.7-2.

9.7.2.7 Airbreathing Propulsion Fuel Tank Inerting. Airbreathing fuel tank inerting is required to protect the system from fuel tank explosion or fire. The inerting could be accomplished by:

- Pretreatment of fuel and filling and pressurizing of inerted tank
- Removal of oxygen during ascent by displacement with bubbled nitrogen.

The latter method is employed in the newer aircraft.

Flammability data are presented in Fig. 9.7-31 (from Parker Hannifin data). The oxygen presently found in aircraft fuel tanks originate from:

- Air injected in the tanks
- Oxygen dissolved in the fuel

The amount of dissolved gas is naturally a function of the pressure on the fuel. Therefore, the shuttle operating at altitude releases oxygen and increases the hazards.

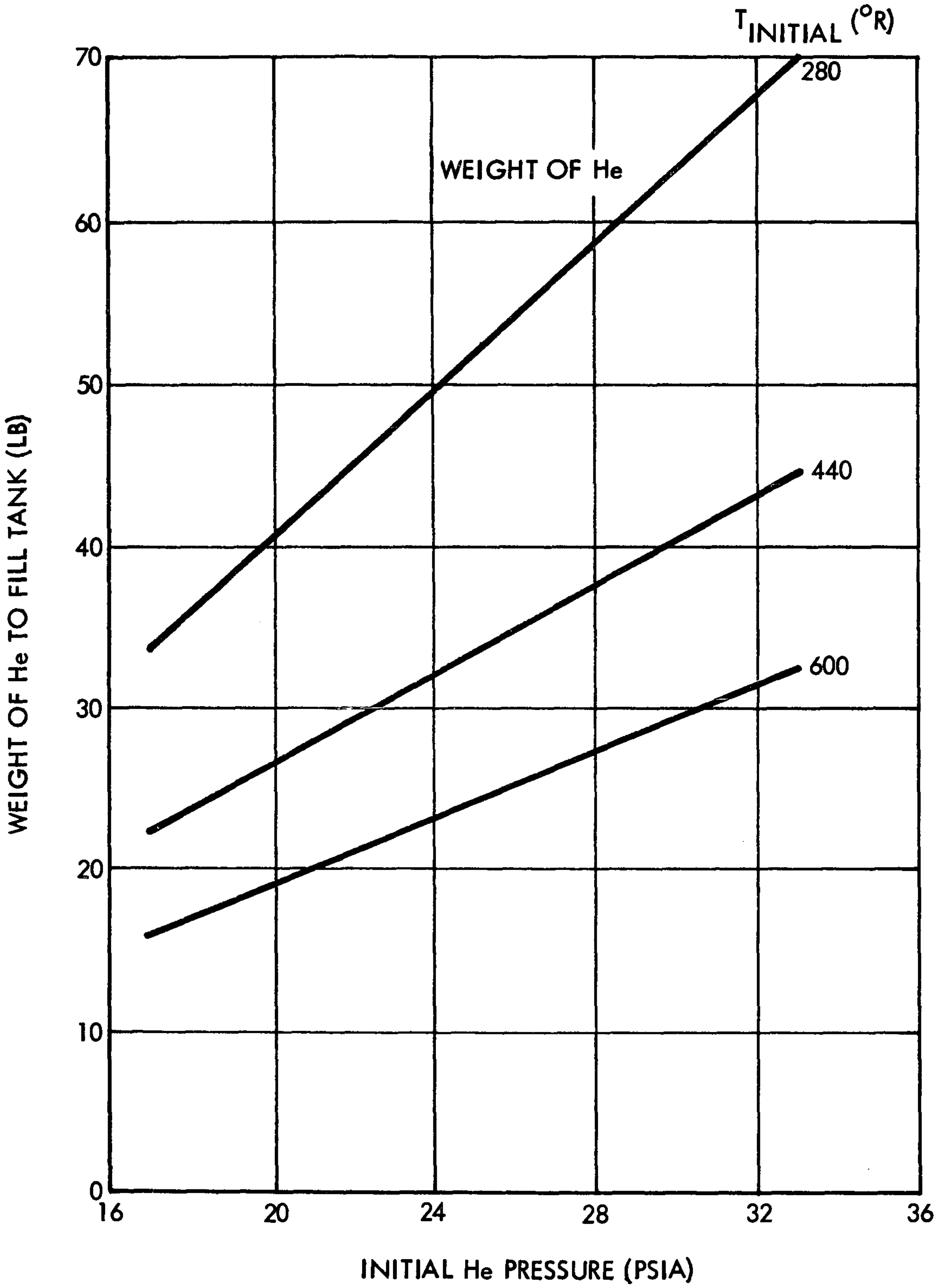

Fig. 9.7-30 OMS LH_2 Tank Helium Inerting Gas Tank Pre-Warmed by Pressurizing H_2

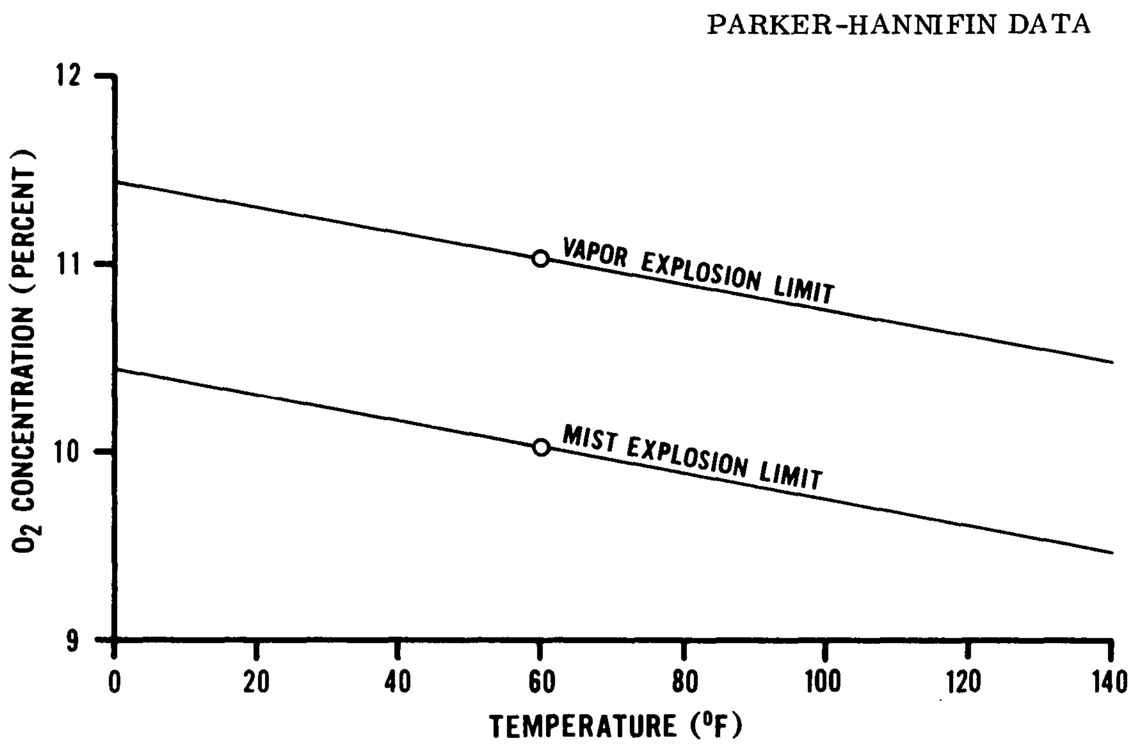

Fig. 9.7-31 Limits of Flammability of JP-4 Vapor-Nitrogen-Air Mixture at 27°C (80.4°F) and Atmospheric Pressure

In the Parker Hannifin process, nitrogen is introduced in bubbles during ascent to remove dissolved oxygen and purge the tanks. Approximately 0.5 lb of nitrogen is required per 1,000 gal of fuel. Also, as the fuel is withdrawn in use, nitrogen is used for pressurization. This requires approximately 10 lb for the orbiter.

9.7.2.8 Analysis of the Ground Purging System. An analysis was made to present parametrically the variables associated with the design of the N_2 distribution system for inerting hydrogen leaks and purging vehicle compartments during the prelaunch mission phase. Nitrogen is used to dilute the hydrogen leakage to a concentration low enough to assure a nonexplosive atmosphere. The main sources where H_2 leakage occurs are the H_2 tanks, valves, fill areas, and vent areas. Systems which use H_2 include the OIPS, OMPS, ACPS, APU, and the Fuel Cells. Since these systems are distributed throughout the vehicle, an extensive N_2 distribution system is needed to deliver the N_2 to the many and dispersed potential H_2 leak points.

The primary variables associated with the N_2 distribution system include, mass flowrate, delivery pressure, line inlet pressure, line diameter, and line length. Total mass flowrate ranges from 5-40-20 lb/sec. The delivery pressure is slightly greater than the sea level ambient (as a minimum) and the line lengths can be as long as 100 feet. Line diameter and required inlet pressure are related and can be shown parametrically for fixed values of the other three variables (i.e., flowrate, line length, and delivery pressure). The delivery system can be designed to operate at low pressure (slightly above sea level ambient or high pressure, i.e. above 50 lb/in^2). Figure 9.7-32 shows the minimum diameter, D* (corresponding to choked flow in the line) as a function of stagnation pressure in the line for various flowrates ranging from 2 lb/sec to 20 lb/sec. From this figure, it can be seen that for low pressures (less than 50 lb/in^2), the minimum line diameter requirements increase rapidly. For moderate pressures (50-to-200 lb/in^2), the minimum line diameters are significantly lower. In order to maintain these moderate pressures in the lines, which are feeding into a compartment that is at a pressure of 15 lb/in^2, an

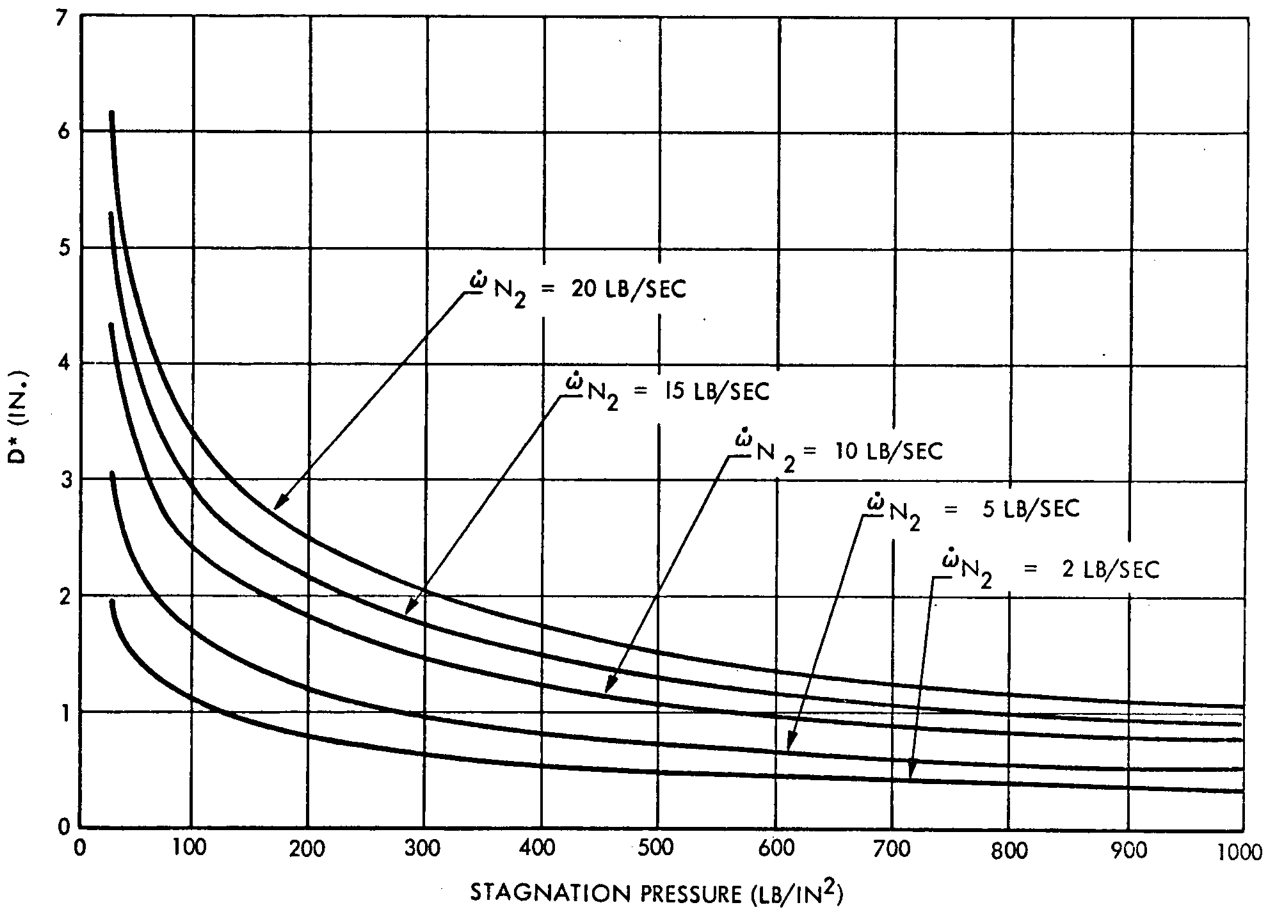

Fig. 9.7-32 Effects of Line Stagnation Pressure and Flowrates on Minimum Line Size

orifice (operating in a choked flow mode) is located near the exit of all distribution lines.

For a distribution system operating at moderate pressures, the required inlet pressure (to overcome friction in the line) was determined and is shown in Fig. 9.7-33. These curves are based on a line length of 100 feet and a stagnation pressure of 50 psia at the end of the line. Various flowrates were considered ranging from 1-to-20 lb/sec. It was assumed for these curves that the flowrates shown occur over the full 100-ft length, if flow is diverted from the main distribution line (as it is in the real case). The required inlet pressures will be lower than those shown. The left end of the curves correspond to choked flow in the lines; and as the line diameter is increased, the maximum Mach number in the line decreases. As can be seen, a small increase in line size decreases the pressure drop significantly, and when the line diameter is increased by about 1 inch over the minimum, the pressure drop decreases to 10 psi or less and could almost be considered negligible. The 50-psia minimum stagnation pressure was selected to assure that the orifice located at the end of the line always will be choked. Thus, the flowrates to the various distribution points can be controlled with relative ease by controlling inlet pressure and orifice diameters.

9.7.3 Purging, Inerting, and Pneumatic Subsystem Tradeoff Studies

The Purging, Inerting, and Pneumatic Supply Subsystem tradeoff studies were performed to provide comparison of the various alternatives that result from the design approach requirements.

9.7.3.1 Helium Subsystem Alternatives. Employing the helium requirements presented in Table 9.7-1, three subsystem alternatives were examined as presented in Table 9.7-3. The alternatives presented in this table principally vary in the requirements for bag purging. (Two tankage weights are shown for storage at LH_2 temperatures. The weights without parenthesis are titanium tanks and those with parenthesis are aluminum tanks.)

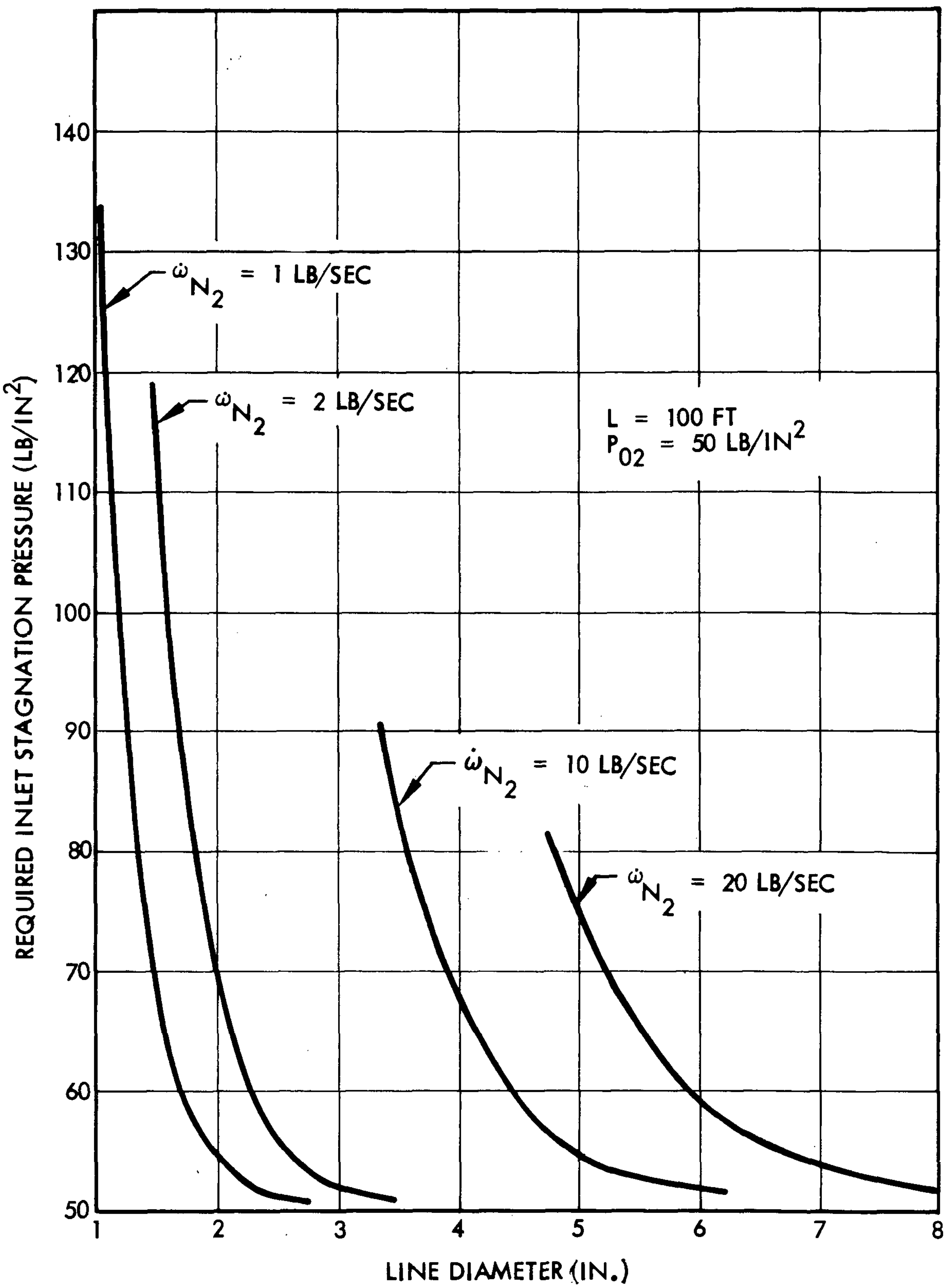

Fig. 9.7-33 Effects of Flowrate and Line Size on Inlet Pressure Requirements

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Table 9.7-3

PURGING, INERTING, AND PNEUMATIC SUPPLY—HELIUM SUBSYSTEM ALTERNATIVES

Item	(1) With LH_2 in OMPS Tank During Reentry (2) With Recirculation of Purge Bag He		(1) With LH_2 in OMPS Tank During Reentry (2) No Recirculation of Purge Bag He		W/O LH_2 in OMPS Tank During Reentry or Vacuum-Jacketed	
	Storage at LH_2 Temperature	Ambient Storage	Storage at LH_2 Temperature	Ambient Storage	Storage at LH_2 Temperature	Ambient Storage
Helium Requirements Conditioning Reactants:	80	80	72	72	70	70
O_2	127	127	12	14	12	14
H_2	127	127	12	14	12	14
Tankage	310 (920)	1,060	280 (820)	1,060	270 (800)	1,040
Components	402	408	327	333	327	333
Residual Helium	133	33	125	25	122	24
Total Dry	712 (1,322)	1,468	607 (1,147)	1,393	596 (1,147)	1,373
Total Fluid	467	367	221	125	216	122
Total	1,179 (1,789)	1,835	828 (1,368)	1,518	812 (1,343)	1,495

9.7.3.2 Nitrogen Subsystem Alternatives. There are a number of possible combinations of nitrogen subsystem alternatives. The requirements in Table 9.7-2 were employed. Subsystem comparisons are presented in Table 9.7-4.

Case I presents the minimum requirement - no insulation or hydrogen leakage purging. Case II adds insulation purging. There is a large increase in requirements with Case III with hydrogen leakage purging (including OIPS). Tank inerting in Case IV results in the maximum weights.

Case V has been presented as a special case, in which leakage purging is performed for all cryogenic subsystems except the OIPS. (This would be the case for a shuttle with droptanks.)

9.7.3.3 Ground Purging Subsystem Considerations. A study was made to determine the operating pressures, line sizes, and number of main distribution lines using the data previously presented. Since low pressures (slightly above 15 lb/in^2) result in large line sizes, whereas moderate pressures (~50-200 lb/in^2) result in much smaller line sizes, a moderate operating pressure is selected for this application. A delivery pressure of 50 lb/in^2 is selected, which is high enough to assure that the orifices located in the branch lines are always in a choked flow-operating condition. This eases the control of flow to the various locations within the vehicle to which N_2 needs to be delivered. The pressure drops associated with a flowrate of 10 or 20 lb/sec in a 100-ft line are not excessive as long as the line size is large enough so that choking does not occur in the line due to friction. This condition can be accomplished by sizing the line greater than

3.50 in. for 10 lb/sec flow and 4.75 in. for 20 lb/sec flow. For a 3.50 in. line flowing 10 lb/sec over 100-ft length and delivering the N_2 at 50 lb/in^2, the resulting required inlet pressure is less than 85 lb/in^2. Correspondingly, for a 4.75 in. line, 20 lb/sec, the resulting required inlet pressure is less than 80 lb/in^2. Both of these pressure and line size combinations are such as to result in a minimum gage aluminum line. Since the lines are minimum gage, the line weight per unit length of the 4.75-in. line is 36 percent heavier than that for a 3.50-in. line. However, if two 3.50-in. lines are used instead of one 4.75-in. line, the dual line system would weigh almost 50 percent more than the single line system. Therefore, a lighter main distribution line weight results if a single line is used. However, the detail design of the vehicle may preclude the use of a single feed line for inerting and purging if insufficient room is available between the tanks and structure to run the small side branches completely around the tanks. In this case, two main feed lines may be necessary, one on either side of the tanks.

	CASE I			CASE II			CASE III			CASE IV			CASE V		
	(1) Vacuum-Jacketed OMPS Tanks (2) W/O H_2 Leakage Purging (3) W/O H_2 Tank Inerting			(1) W/O H_2 Tank Inerting (2) W/O H_2 Leakage Purging			(1) W/O H_2 Tank Inerting (2) With H_2 Leakage Purging			(1) With H_2 Tank Inerting (2) With H_2 Leakage Purging			(1) W/O H_2 Tank Inerting (2) W/O OIPS Leakage Purging		
	Sub-Critical	Super-Critical	Ambient Storage	Sub-Critical	Super-Critical	Ambient Storage	Sub-Critical	Super-Critical	Ambient Storage	Sub-Critical	Super-Critical	Ambient Storage	Sub-Critical	Super-Critical	Ambient Storage
N_2 Requirements:															
Inerting	11	11	11	11	11	11	10	10	10	1,980	1,980	1,980	10	10	10
Purging	-	-	-	4	4	4	1,323	1,323	1,323	402	402	402	89	89	89
Total N_2	11	11	11	15	15	15	1,333	1,333	1,333	2,382	2,382	2,382	99	99	99
Conditioning Reactants: *															
O_2				0.8	0.77	0.77	66	65	65	118	116	116	4.6	4.5	4.5
H_2				0.8	0.77	6.77	66	65	65	118	116	116	4.6	4.5	4.5
Tankage	2	3	20	2.25	4.25	27	25	250	2,300	45	444	4,120	5	18	140
Other Components	90	138	113	170	183	158	213	203	179	269	238	214	213	203	179
Trapped N_2	-	-	-	-	-	-	26	119	18	47	211	30	2	8	1.5
Total Dry Weight	92	141	133	172.25	187.25	185	238	453	2,479	314	682	4,334	218	221	319
Total Fluid Weight	11	11	11	16.6	16.5	16.5	1,491	1,582	1,481	2,665	2,825	2,644	116	116	110
Total Weight (lbm)	103	152	144	189	204	202	1,729	2,035	3,960	2,979	3,507	6,978	328	337	429

*Weight of reactants required to condition the nitrogen.

Table 9.7-4 PURGING, INERTING, AND PNEUMATIC SUPPLY NITROGEN SUBSYSTEM ALTERNATIVES